National Aeronautics and
Space Administration

Exploration Systems Development Mission Directorate (ESDMD)

HEOMD-006

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EXPLORATION SYSTEMS DEVELOPMENT MISSION DIRECTORATE UTILIZATION PLAN

This document has been reviewed for Proprietary, CUI, and Export Control (ITAR/EAR) and has been determined to be non-sensitive. It has been released to the public via the NASA Scientific and Technical Information (STI) Process DAA #20220005087

This document was approved by NASA's Exploration Systems Development Mission Directorate (ESDMD), Space Operations Mission Directorate (SOMD), Science Mission Directorate (SMD), Space Technology Mission Directorate (STMD)

March 2022

REVISION AND HISTORY PAGE

Revision No.	Change No.	Description	Release Date
-	HEO-0015	Initial Release (Reference CR HEO-C0015), approved at a Quad-Directorate Program Management Council (DPMC) on October 4, 2021 (ESDMD, SOMD, SMD, STMD)	10/04/2021
A	HEO-0019	Adds Appendix 1 to Initial Baseline (Reference CR HEO-C0019), approved at a Quad-Directorate Program Management Council (DPMC) on February 22, 2022 (ESDMD, SOMD, SMD, STMD)	02/22/2022

This document has been approved for public release per DAA #20220005087.

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1.0 INTRODUCTION

1.1 PURPOSE

The purpose of the Human Exploration and Operations (HEO) Utilization Plan is to identify and describe NASA's science and technology utilization goals and objectives that will be enabled by human missions. These goals and objectives have been defined by NASA's Science Mission Directorate (SMD), Space Technology Mission Directorate (STMD), and HEO Mission Directorate (HEOMD). The overarching goals will be used in several ways. They will help enable and expand NASA's capability to achieve human exploration campaigns. Additionally, the goals and objectives will be used to identify how human missions will support the science and technology communities to conduct fundamental research about our universe and solve the scientific and technological challenges for sustaining and expanding human exploration campaigns.

1.2 SCOPE

The scope of the Utilization Plan is applicable to Artemis lunar exploration missions; SMD, STMD, and HEOMD utilization goals for HEOMD platforms; and agency exploration strategy using the International Space Station (ISS), the Gateway, Human Landing System (HLS), and lunar missions to prepare for future missions to Mars. The utilization goals and objectives are implemented through science and technology activities across the ISS, Commercial low-Earth orbit (LEO) utilization, the Artemis campaign to cis-lunar space and the lunar surface, and the campaign for the first human missions to Mars. It will be revised and updated to align with mission directorate strategic goals and objectives as the Moon to Mars campaign evolves. Future revisions of this document will capture strategic objective updates from the mission directorates and additional details as the human spaceflight platforms and campaigns evolve.

Utilization is the use of the platform and/or mission to conduct science, research, development, test and evaluation, public outreach, education, and commercialization. Utilization is distinct from the carriers designed to sustain the mission and health of the crew, which include launch vehicles, transportation vehicles, orbital modules, and space suits (carrier and payload definitions per NPR 8705.4).

1.3 RELATIONSHIP TO OTHER DOCUMENTS

NASA's exploration strategy defines a set of evolving capabilities for LEO and human exploration of the Moon, Mars, and beyond. Administration-level human exploration goals are described in NASA's Strategic Plan and other Administration documentation (e.g., *NASA's Plan for Sustained Lunar Exploration and Development*).

HEOMD-007, *HEOMD Strategic Campaign Operations Plan for Exploration (SCOPE)*, translates these higher-level documents into HEOMD goals and exploration strategy. This HEOMD Utilization Plan provides the cross-mission directorate utilization goals and objectives for NASA's human exploration programs and exploration campaigns in HEOMD-007, from LEO to the lunar surface, to Mars, and beyond.

HEOMD-004, *Human Exploration Requirements,* documents requirements affecting the overall exploration campaign or major elements that are derived from this document. However, many utilization capabilities evolve through an iterative process of defining the capabilities needed and the phasing of those needs to enable implementation plans in the other mission directorates at greater detail than would be incorporated in HEOMD-004.

Certain requirements within HEOMD-003, *Crewed Deep Space Systems Human Rating Certification Requirements and Standards for NASA Missions,* may apply to elements provided by HEO, STMD, and/or SMD if they are deemed to be part of the deep space crewed system (e.g., lunar surface systems that interact with the crew). In such cases, HEOMD will work with the appropriate mission directorate(s) to determine the applicable requirement(s) and ensure proper flowdown and information flow.

HEOMD-006, *Human Exploration and Operations Utilization Plan*, is a multi-directorate integrated utilization plan that includes mission-specific utilization plans for the three directorates to enable early coordination and documentation of utilization requirements derived from utilization objectives. HEOMD-006 is structured to include a set of annexes to facilitate revisions and updates as mission architectures, technologies, and individual mission utilization requirements continue to be defined and formulated. The annexes provide more detailed information about high-level utilization cornerstone capabilities that are needed to achieve the objectives and a multi-mission/multi-year context for planned utilization. They include integrated utilization updates for both LEO and Artemis exploration missions. The plan supports joint planning and implementation of utilization using Annexes 2 through 4.

1.4 CHANGE AUTHORITY RESPONSIBILITY

Change authority for this document will be the Associate Administrator (AA) of the Human Exploration and Operations Mission Directorate in accordance with HEOMD-002, *HEOMD Configuration Management Process*, and requires the concurrence of AAs of Partnering Mission Directorates. Partnering Mission Directorates have the authority to call for an update of this document based upon changing goals, priorities, and contexts.

2.0 DOCUMENTS

2.1 APPLICABLE DOCUMENTS

The following documents include specifications, models, standards, guidelines, handbooks, and other special publications. The documents listed in this paragraph are applicable to the extent specified herein.

TABLE 2.1-1 APPLICABLE DOCUMENTS

Document Number	Document Revision	Document Title
HEOMD-002	Baseline May 22, 2017	HEO Configuration Management Process
HEOMD-003	Baseline March 9, 2021	Deep Space Systems Human Rating Certification Requirements and Standards for NASA Missions

Document Number	Document Revision	Document Title
HEOMD-004	Revision B, March 16, 2021	Human Exploration and Operations (HEO) Requirements
HEOMD-004	Revision C, Dec. 14, 2021	Human Exploration and Operations (HEO) Requirements
HEOMD-004	Revision D, TBD	Human Exploration and Operations (HEO) Requirements
HEOMD-007	Baseline, Sep. 28, 2021	HEO Strategic Campaign Operations Plan for Exploration (SCOPE)
HEOMD-410	TBD	Lunar Traverse Data Book
HEOMD-411	TBD	Candidate Utilization Instruments for Lunar Terrain Vehicle (LTV) and Pressurized Rover (PR)
HEOMD-412	TBD	Candidate Capabilities for Utilization Instruments and Sample Collection with a Robotic Arm
HEOMD-413	TBD	Utilization Sample Return Conditioned Transportation Needs for Artemis Capabilities
HEOMD-414	TBD	Lunar Utilization Sites Data Book

2.2 REFERENCE DOCUMENTS

The following documents contain supplemental information to guide the user in the application of this document.

TABLE 2.2-1 REFERENCE DOCUMENTS

Document Number	Document Revision	Document Title
HEO-DM-1002	Sep. 28, 2020	HEO Systems Engineering & Integration (SE&I)-*Mars Mission Duration Guidance for Human Risk Assessment and Research Planning Purposes*
HEO-DM-1004	Jan. 21, 2021	HEO Systems Engineering & Integration (SE&I)-*Planning Guidance for Artemis Mission Durations as Testbeds to Reduce Risks for Human Missions to Mars*
HEOMD-405	Mar. 19, 2021	ESDMD Integrated Exploration Capabilities List
https://doi.org/10.17226/12951	2010	National Academy of Sciences Decadal: New

Document Number	Document Revision	Document Title
		Worlds, New Horizons in Astronomy and Astrophysics
https://doi.org/10.17226/13060	2013	National Academy of Sciences Decadal: Solar and Space Physics: A Science for a Technological Society
https://doi.org/10.17226/13117	2012	National Academy of Sciences Decadal: Vision and Voyages for Planetary Science in the Decade 2013-2022
https://doi.org/10.17226/24938	2018	National Academy of Sciences Decadal: Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space
N/A	Jun. 2020	Artemis Science Plan
N/A	2016	Lunar Exploration Assessment Group (LEAG) Lunar Exploration Roadmap (LER)
N/A	2007	Science Context for Exploration of the Moon (SCEM)
N/A	2018	LEAG Advancing Science of the Moon Specific Action Team Report
N/A	Feb. 2018	NASA Strategic Plan (2018)
NASA/SP-2020-05-2853-HQ	Sep. 2020	Artemis Plan
NASA/SP-20205009602	Dec. 7, 2020	Artemis III Science Definition Team Report
NNH19ZCQ001K_APPENDIX-H-HLS	Oct. 2019	Next Space Technologies for Exploration Partnerships-2 Appendix H: Human Landing Systems
a_sustained_lunar_presence_nspc_report4220final.pdf (nasa.gov)	June 2020	NASA's Plan for Sustained Lunar Exploration and Development
TBD	TBD	HEOMD Human Research Program's Path to Risk Reduction (PRR)
TBD	TBD	Human Research Program (HRP) Candidate Test Objectives (CTOs)

Document Number	Document Revision	Document Title
TBD	TBD	Environmental Control and Life Support System Crew Health and Performance (ECLSS-CHP) Strategic Capability Leadership Team (SCLT) Roadmaps
NID 8715.129	Jul. 9, 2020	Biological Planetary Protection for Human Missions to Mars
NPD 8020.7	May. 17, 2013	Biological Contamination Control for Outbound and Inbound Planetary Spacecraft
NPR 8715.24	Sep. 24, 2021	Planetary Protection Provisions for Robotic Extraterrestrial Missions
NASA/TM-20205008626	Oct. 2020	Lunar Water ISRU Measurement Study (LWIMS): Establishing a Measurement Plan for Identification and Characterization of a Water Reserve
https://humanresearchroadmap.nasa.gov/architecture/	2020	Human Research Roadmap
https://science.nasa.gov/science-pink/s3fs-public/atoms/files/GapAnalysisReport_full_final.pdf	Apr. 2021	Space Weather Science and Observation Gap Analysis for NASA
https://spp.fas.org/eprint/protection.pdf	Dec. 2020	National Strategy for Planetary Protection
NASA/Presentation- 20210014156	Apr. 21, 2021	Space Weather Architectures for NASA Missions
NASA/Presentation- 20210020463	Aug. 12, 2021	An Assessment of Space Weather Architectures to Support Deep Space Exploration
https://www.nasa.gov/nesc/workshops/safe-human-expeditions-beyond-leo	TBD	Safe Human Expeditions Beyond Low-Earth Orbit Workshop Report

3.0 HUMAN EXPLORATION UTILIZATION GOALS AND OBJECTIVES

The Utilization Goals and objectives described in Table 3.0-1 are supported by the overarching Human Exploration Goals and Objectives that are outlined in the HEOMD-007 SCOPE document (i.e., Section 3). The individual objectives come directly from the respective Mission Directorates (SMD, STMD, HEOMD). They broadly support the Space Policy Directive-1 instruction to NASA to "Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations..."

The individual objectives are implemented through science and technology activities across the International Space Station Program, Commercial LEO utilization, the Artemis campaign to cis-lunar space and the lunar surface, and the Moon-to-Mars campaign. For each objective, a table specifies the relevant program/project/locations that are central to the fulfillment of the utilization objective. If a program is not central to the objective fulfillment, it is not specified in the table. The tables may change in future revisions of this document as the utilization goals and objectives become better defined.

Future revisions of this document will capture Mars transit and Mars surface exploration utilization goals and objectives.

Order of appearance of objectives does not denote any relative priority of the objective.

TABLE 3.0-1 SUMMARY OF HUMAN EXPLORATION UTILIZATION GOALS BY NASA MISSION DIRECTORATE

Mission Directorate		Utilization Goals
3.1 SMD	SMD Utilization Goal 1	Enable scientific investigations from the lunar surface, including field relationships, in-situ observations, and sample return, to address the multidisciplinary objectives of the Science Mission Directorate
	SMD Utilization Goal 2	Enable scientific investigations from human spaceflight platforms to address the multidisciplinary objectives of the Science Mission Directorate
	SMD Utilization Goal 3	Enable science investigations on the surface of Mars, in Mars orbit, and in Mars transit
3.2 STMD	STMD Utilization Goal 1	Enable sustainable living and working farther from Earth (“Live”)
	STMD Utilization Goal 2	Enable transformative missions and discoveries (“Explore”)
3.3 HEOMD	HEOMD Utilization Goal 1	Advance knowledge to support safe, productive human space travel, and enable systems development and testing to reduce health and performance risks for future human exploration
	HEOMD Utilization Goal 2	Advance the operational capabilities required for sustainable lunar operations and the first human missions to Mars including demonstrating approaches to planetary protection.
3.4 NASA Multi-directorate	Multi-directorate Utilization Goal 1	Enable commercial, interagency, and international partnerships to make space exploration more affordable and sustainable, grow new markets, and increase capabilities

3.1 SMD UTILIZATION GOALS AND OBJECTIVES

The Science Mission Directorate addresses high-priority science objectives to understand 1) the origin and evolution of both the Earth-Moon system and the broader solar system, 2) the nature of the Sun, how it influences the nature of space and the atmospheres of planets and the technology that exists there, 3) the dynamic and complex processes that shape our home planet, 4) how the universe began and evolved, and 5) biological and physical systems in the exploration environments to advance fundamental knowledge and enable human space missions. SMD goals and objectives below are aligned with key science goals defined in National Academy of Sciences and LEAG documents (e.g., *Scientific Context for Exploration of the Moon*, *Lunar Exploration Roadmap,* and *National Academy of Sciences Decadal Surveys*). SMD is responsible for the identification, prioritization, and implementation of these objectives, working with HEOMD to integrate the objectives within vehicle and mission capabilities, and will continue to update them as discoveries are made and the campaign evolves. Additional Mars science and technology goals will be defined in future revisions of this document.

3.1.1 SMD Utilization Goal 1

Enable scientific investigations from the lunar surface, including field relationships, in-situ observations, and sample return, to address the multidisciplinary objectives of the Science Mission Directorate.

3.1.1.1 SMD Objective 1.1: Understanding Planetary Processes

A key motivation for studying the Moon is to better understand the origin and evolution of terrestrial planets, including the Earth. The Moon is a small planetary body that has not experienced modifications through plate tectonics such as those seen on Earth. Therefore, the Moon provides access to study a wide variety of planetary processes that include, but are not limited to, planetary differentiation (formation of the magma ocean, crust, mantle and core), volcanism (partial melting, magma production, eruptions, flow sequence and compositions), impact processes (basins, craters, mixing of the crust, and formation of regolith), volatiles (history, production, and escape), and tectonism (deformation of the crust and thermal history).

NASA’s current and planned programs will provide the means to study these processes and to meet other planetary science objectives. These objectives, along with the program/mission segment/element and location of the study area, are listed below.

Relevant program/project/location:

Lunar surface	HLS, Lunar Terrain Vehicle (LTV), future surface assets
Lunar transit and orbit	Gateway, Orion
Low-Earth orbit	N/A

Applicable investigations:

a. Understand formation of the Earth-Moon system.

b. Understand planetary differentiation and evolution on the Moon: The formation of the magma ocean, crust, mantle, and core.

c. Understand volcanic processes: Partial melting, eruptions, flow sequences and compositions.

d. Understand tectonism on the Moon: The deformation of the crust and the Moon's thermal history.

e. Understand impact processes on the Moon: Basin and crater formation and modification, mixing of regolith and crustal components, and crustal stratigraphy.

f. Understand the characteristics, evolution, and space weathering of lunar regolith and dust.

3.1.1.2 SMD Objective 1.2: Understanding the Character and Origin of Lunar Volatiles

Lunar polar volatiles are of high priority for both science and exploration. The lunar polar cold traps provide an unprecedented record of solar system volatiles delivered from numerous sources (e.g., comets, asteroids, solar wind interactions, interior outgassing) over an extended period of time. Exploring the lunar polar regions is key to understanding the behavior and history of volatiles on our Moon as well as other airless bodies in the solar system. The investigations listed below address this objective. These investigations require access to volatile-rich terrains, including persistently shadowed and cold regions around the lunar poles, and the development of sampling strategies, surface and subsurface instrumentation for measurements, appropriate sealed sample containment for samples, and sample return and curation plans.

Relevant program/project/location:

Lunar surface	HLS, LTV, future surface assets
Lunar transit and orbit	Gateway, Orion
Low-Earth orbit	N/A

Applicable investigations:

a. Determine the compositional state (elemental, isotopic, mineralogic) and the abundance and compositional distribution (lateral and with depth) of the volatile component in lunar polar regions.

b. Determine the source(s) for lunar polar volatile deposits.

c. Understand the transport, retention, alteration, and loss processes that operate on volatile materials near and at permanently shadowed lunar regions.

d. Understand regolith modification processes, including space weathering, particularly deposition of volatile materials in the near surface.

e. Determine how water vapor and other volatiles are released from the lunar surface and migrate to the poles where they are adsorbed in polar cold traps.

f. Document and understand the impact of exploration activities on the lunar volatile record.

3.1.1.3 SMD Objective 1.3: Interpreting the Impact History of the Earth-Moon System

The surface of the Moon provides an exceptional record of impact crater formation extending from the earliest period of the solar system to the present day. This lunar impact history is relevant not just to untangling the geologic evolution of the Moon, but to the solar system as a whole. Remotely sensed, geophysical, and sample data enable investigations that test and refine models established for lunar origin and evolution. Dating formation of large impact basins will relate directly to the crustal evolution of all the terrestrial planets and, possibly, to the bombardment history of the outer solar system. Well-preserved craters on the Moon are a natural laboratory to understand the impact rates of the Earth-Moon system, the impact processes at a large range of scales, and to provide an absolute chronology that anchors the impact history of the inner solar system through returned lunar samples linked to specific geologic units. The lunar cratering history can be extrapolated to other planets in the inner solar system. The following investigations address this objective.

Relevant program/project/location:

Lunar surface	HLS, LTV, future surface assets
Lunar transit and orbit	Gateway, Orion
Low-Earth orbit	N/A

Applicable investigations:

a. Test the cataclysm hypothesis (Late Heavy Bombardment, 3.9-4.1 Gya).

b. Understand changing compositions of impactors with time and the nature of the early Earth.

c. Understand changes to Earth-Moon bombardment in the post-basin era.

d. Understand the impact history of the landing site(s).

3.1.2 SMD Utilization Goal 2

Enable scientific investigations from human spaceflight platforms to address the multidisciplinary objectives of the Science Mission Directorate.

3.1.2.1 SMD Objective 2.1: Revealing the Record of the Ancient Sun and Our Astronomical Environment

The airless Moon—with its ancient crust—serves as a witness plate that captures processes taking place in space. The interaction of the solar wind, cosmic rays, and meteoroid bombardment with the regolith on the surface of the Moon changes the chemical, isotopic, and petrographic makeup of the regolith. By studying preserved paleoregolith horizons, one can construct a timeline or history of processes that are important to the study of many of the bodies in our solar system, including the Sun.

Relevant program/project/location:

Lunar surface	HLS, LTV, future surface assets

Lunar transit and orbit	Gateway, Orion
Low-Earth orbit	ISS, Commercial LEO

Applicable investigations:

a. Understand the history of the Sun, including the composition and flux of the solar wind.

b. Understand the record of solar energetic particles, cosmic rays, gamma-ray bursts, and supernova.

c. Understand the long-term variability in the solar constant.

3.1.2.2 SMD Objective 2.2: Observing the Earth, the Local Space Environment and Universe from a Unique Location

A robust human and robotic exploration program provides unique opportunities to employ the human missions as platforms for high-priority astrophysics, heliophysics, and Earth science investigations.

The Moon's position relative to Earth's magnetosphere makes it an excellent location to study the solar wind and the dynamics of the deep magnetotail, to characterize atmospheric losses and the effects of the Moon on the local plasma environment, and to perform observations of the Sun and extra-solar system planets over a broad frequency spectrum. The Moon further provides a laboratory for interdisciplinary investigations of the charged interactions of dust grains with plasmas and extreme ultraviolet photons. Astrophysical and space weather studies may be performed from the Moon, especially at frequency ranges not favorable for ground- and space-based telescopes. In particular, the surface of the radio-quiet far side of the Moon offers unique opportunities for long wavelength radio astronomy and for short wavelength solar radio observations. Furthermore, the surface of the Earth-facing near side of the Moon provides unique opportunities to acquire highly precise lunar position measurements via laser ranging with implications for fundamental physics.

Additionally, parallel studies conducted on the lunar surface, in cis-lunar space (e.g., Gateway), on LEO platforms (e.g., ISS), and on Earth can provide a more comprehensive understanding of space weather phenomena within and outside of Earth's protective magnetosphere.

Relevant program/project/location:

Lunar surface	HLS, LTV, future surface assets
Lunar transit and orbit	Gateway, Orion, future long-duration orbital habitat
Low-Earth orbit	ISS, Commercial LEO

Applicable investigations:

a. Conduct astrophysics and basic physics investigations.

b. Conduct heliophysics investigations using platforms on the surface of the Moon and in cis-lunar and LEO and use enabling infrastructure for off-Sun-Earth-line heliocentric solar observations:

1. Understand space weather phenomena to enable improved prediction of the dynamic space environment for deep space exploration.
2. Understand the dynamics of the deep magnetotail from the Moon's unique position relative to Earth's magnetosphere.
3. Understand the Moon's plasma environment and its impact on the lunar exosphere and surface, including dust-plasma interactions.

c. Use the Moon, cis-lunar space, and LEO as platforms for Geospace- and Earth-observing studies.

3.1.2.3 SMD Objective 2.3: Conducting Experimental Science in the Lunar and LEO Environments

The Moon has a unique combination of environmental characteristics that are not attainable on the Earth or by utilizing LEO research platforms. Biological and physical sciences have common lunar environmental factors that are central for their research investigations, which include radiation, one-sixth gravity, regolith, dust, and absence of a magnetic field. This environment enables biological and physical scientists to address high-priority scientific objectives, questions, and knowledge gaps that are important for understanding human hazards and risks of space exploration and for developing technologies and other applications for sustained, long-duration exploration. Additionally, parallel studies may be conducted on the lunar surface, Gateway, LEO platforms (e.g., ISS), and on Earth to obtain a comprehensive understanding of environmental factor impacts on biological and physical systems and for modeling of the resulting effects. Space biological and physical sciences research the objectives listed below.

Relevant program/project/location:

Lunar surface	HLS, LTV, future surface assets
Lunar transit and orbit	Gateway, Orion, future long-duration orbital habitat
Low-Earth orbit	ISS, Commercial LEO

Applicable investigations:

a. Understand the effects of acute and long-duration exposure to the lunar environment, gravity, and radiation on physical and biological systems.

b. Understand physical phenomena in the unique environment of the lunar surface and how those phenomena can be used in support of In-Situ Resource Utilization (ISRU), power, propulsion, and human support systems.

c. Understand the mechanical and electrical properties of lunar dust relevant to modeling dust transport, contamination, and cleaning of surfaces.

d. Utilize the unique environment of the lunar environment for fundamental physics research.

e. Understand the effects of the lunar environment on microbiology, microbial populations, biofilms, community dynamics, and the microbiome of the built environment and organisms.

f. Understand the effects of the lunar environment on crop plant physiology and the potential for using in-situ lunar resources to grow plants.

3.1.3 SMD Utilization Goal 3

Enable science investigations on the surface of Mars, in Mars orbit, and in Mars transit.

3.2 STMD UTILIZATION GOALS AND OBJECTIVES

STMD provides technology to enable HEOMD and SMD utilization objectives. The following STMD goals result from the STMD review process (e.g., STMD's Strategic Technology Architecture Roundtable) and include pursuing technology demonstrations in the following areas. Additional definition on these outcomes will be provided as use cases are developed.

STMD is responsible for the technology infusion and/or implementation of utilization to meet these objectives, working with HEOMD to integrate the objectives within vehicle and mission capabilities, and will continue to update them as the campaign evolves. Mars technology goals will be defined in future revisions of this document.

3.2.1 STMD Utilization Goal 1

Enable sustainable living and working farther from Earth ("Live").

3.2.1.1 STMD Objective 1.1: Develop exploration technologies and enable a sustainable Space Economy with supporting utilities and commodities

Relevant program/project/location:

Lunar surface	HLS, LTV, future surface assets
Lunar transit and orbit	Gateway
Low-Earth orbit	N/A

Example lunar surface technologies:

a. Sustainable power sources and other surface utilities to enable continuous lunar and martian surface operations

b. Commercial-scale ISRU production/utilization capabilities, including sustainable commodities on the lunar and martian surfaces

c. Technologies that enable surviving the extreme lunar and martian environments

d. Autonomous excavation, construction, and outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in-situ resources

STMD objectives for other human spaceflight platforms will be added as needed in future updates.

3.2.1.2 STMD Objective 1.2: Enable long-duration human exploration missions with Advanced Life Support & Human Performance technologies

Relevant program/project/location:

Lunar surface	HLS, LTV, future surface assets
Lunar transit and orbit	Gateway, future long-duration orbital habitat, Orion
Low-Earth orbit	ISS, Commercial LEO

Example life support and human performance technologies – ^**TBD-001**^

3.2.2 STMD Utilization Goal 2

Enable transformative missions and discoveries ("Explore").

3.2.2.1 STMD Objective 2.1: Demonstrate next generation high performance computing, communications, and navigation for deep space environments

Relevant program/project/location:

Lunar surface	HLS, LTV, future surface assets
Lunar transit and orbit	Gateway, future long-duration orbital habitat
Low-Earth orbit	ISS, Commercial LEO

Example technologies – ^**TBD-002**^

3.2.2.2 STMD Objective 2.2: Demonstrate advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions

Relevant program/project/location:

Lunar surface	HLS, LTV, future surface assets
Lunar transit and orbit	Gateway, future long-duration orbital habitat
Low-Earth orbit	ISS, Commercial LEO

Example robotic and autonomy technologies – ^**TBD-003**^

3.3 HEOMD UTILIZATION GOALS AND OBJECTIVES

HEOMD includes the Human Research Program, which conducts an applied scientific research and technology development program, and Exploration Capabilities (EC) technology development program. These HEOMD divisions are responsible for the identification, prioritization, and implementation of their research and technology development objectives on the ground and in human spaceflight missions and working with HEOMD spaceflight programs to integrate their objectives within vehicle and mission capabilities. HRP and EC will continue to update their objectives as discoveries are made and the campaign evolves. Additional Mars science and technology goals will be defined in future revisions of this document.

3.3.1 HEOMD Utilization Goal 1

Advance knowledge to support safe, productive human space travel, and enable systems development and testing to reduce health and performance risks and advance capabilities for future human exploration.

By integrating human spaceflight research and applicable technology development efforts, the aim is to best utilize the ISS, Commercial LEO destinations, and Artemis missions to reduce risks to human health and performance, thus supporting human exploration of Mars. The ISS, Commercial LEO and Artemis missions will enable utilization to develop and test human system risk mitigations in a high-fidelity setting with operational deep space environments and mission durations representative of exploration class/Mars missions to validate risk mitigation strategies.

3.3.1.1 HEOMD Objective 1.1: Exploration Crew Health and Performance (CHP) Operations Advancement—Evaluate and validate progressively Earth-independent crew health and performance systems and operations.

Relevant program/project/location:

Lunar surface	HLS, LTV, Exploration Extravehicular Activity (xEVA), future surface assets
Lunar transit and orbit	Gateway, xEVA, Orion, future long-duration orbital habitat
Low-Earth orbit	ISS, xEVA, Commercial LEO

Artemis crew health and performance systems and operations should be designed for use in a progressively Earth-independent manner, simulating Mars-class mission parameters (e.g., communication delay) to enable astronauts to function autonomously while maintaining their own crew health and performance and mitigating risk for a human mission to Mars. These missions offer a stepping-stone approach to Mars exploration-class missions where the crew health and performance paradigm will be vastly different from ISS, given the reduced evacuation availability/longer return-to-Earth time, limited consumables resupply, and delayed communications.

Commercial LEO should be designed to develop and test a Mars-forward crew health and performance system and operations. ISS should utilize ISS4Mars Use Cases that implement increasingly complex aspects of an exploration crew health and performance system and operations.

This objective will enable implementation and evaluation of innovative crew health and performance capabilities such as a Crew Health and Performance Integrated Data Architecture (CHPIDA), autonomous in-situ analysis and imaging capabilities, real-time determination of food and nutrition system efficacy, real-time pharmaceutical stability determination, integrated physiological and psychological monitoring and countermeasures, and simulations for autonomous intravehicular and extravehicular crew health and performance operations.

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3.3.1.2 HEOMD Objective 1.2: Integrated Human System Research—Evaluate changes to the human system, characterize impacts to overall crew health and performance, and validate countermeasures.

Relevant program/project/location:

Lunar surface	HLS, LTV, xEVA, future surface assets
Lunar transit and orbit	Gateway, xEVA, Orion, future long-duration orbital habitat
Low-Earth orbit	ISS, xEVA, Commercial LEO

Artemis platforms and missions should accommodate comprehensive, extensible in-flight capabilities, and allocate necessary resources to perform targeted and applied human system research. To sustain astronauts' health, well-being, and performance during and after missions, an integrative cross-platform human research strategy is necessary. Artemis missions offer combined spaceflight hazards similar to a Mars mission that support enhanced understanding of human system risks (both individual and teams), the design and validation of human health and performance countermeasures, knowledge, standards, technologies and tools to enable safe, reliable, and productive human space exploration.

Commercial LEO should be designed to perform human system research (on both individual and teams) and provide an isolation and confinement analog habitat.

ISS should accommodate research of varying durations to continue studying the effects of spaceflight hazards.

This objective will enable characterization and evaluation of physiological, cognitive, behavioral, and performance effects on individuals and teams, validation of countermeasures to mitigate risks, and enable a human-systems integration architecture.

3.3.1.3 HEOMD Objective 1.3: Living Environment—Evaluate the interaction of exploration habitation systems and spaceflight hazards and validate effects on crew health and performance.

Relevant program/project/location:

Lunar surface	HLS, LTV, xEVA, future surface assets
Lunar transit and orbit	Gateway, xEVA, Orion, future long-duration orbital habitat
Low-Earth orbit	ISS, xEVA, Commercial LEO

Artemis platforms should accommodate in-flight environmental monitoring and measuring capabilities to characterize the effects of the deep space, operational environment where the crew will be living and working. These data will be analyzed for potential impacts to human health and performance, as well as validate models that inform mission design and operations.

Commercial LEO and ISS should accommodate in-flight environmental monitoring and measuring capabilities to characterize the operational environment where the crew will be living and working.

This objective will enable characterization of the exploration habitat systems with spaceflight hazards, such as space radiation, dynamic loads during launch/landing, hostile and closed environments, and distance from Earth, to determine how these interactions affect overall crew health and performance.

3.3.1.4 HEOMD Objective 1.4: Special Task-Related Issues—Evaluate and validate operational implementation of critical tasks, protocols, procedures, and human factors for optimal crew health and performance.

Relevant program/project/location:

Lunar surface	HLS, LTV, xEVA, future surface assets
Lunar transit and orbit	Gateway, xEVA, Orion, future long-duration orbital habitat
Low-Earth orbit	ISS, xEVA, Commercial LEO

Artemis, Commercial LEO, and ISS should implement in-flight capabilities and necessary resources for evaluating crew task and activity performance to inform Mars-class operations and task/activity planning. Artemis missions should also accommodate systems and capabilities to enable crew-autonomy for conducting mission-critical tasks, including extravehicular activities (EVAs).

This objective will enable validation of crew task/activity planning, procedures, protocols, and human factors involved in nominal and off-nominal mission performance.

3.3.1.5 HEOMD Objective 1.5: Extended Durations—Validate risk mitigation strategies and test crew health and performance systems in the deep-space hazard environment with mission durations and systems representative of Mars-class missions.

Relevant program/project/location:

Lunar surface	HLS, LTV, xEVA, future surface assets
Lunar transit and orbit	Gateway, xEVA, Orion, future long-duration orbital habitat
Low-Earth orbital	ISS, xEVA, Commercial LEO

Artemis platforms' designs, operations, and mission profiles should accommodate extended-duration missions as described in HEO-DM-1004 to reduce risk for Mars-class missions. The recommended Artemis durations correspond to the ISS Complement of Integrated Protocols for Human Exploration Research (CIPHER) study to allow for comparative analysis and validation. While past and future ISS human system data will provide a solid foundation, knowledge and systems will evolve as planners define Artemis missions and crews experience the deep-space hazard environment for longer durations with increasing independence from Earth. Artemis extended- duration missions should also be planned to allow sufficient time between mission complete and an actual Mars mission to evaluate crew health and performance, countermeasures, pre-mission training, operations and systems to apply knowledge gained from longer Artemis missions. Habitable volume and layout of the Artemis vehicle(s) and/or habitat(s), for example, can help to inform vehicle and habitat design for Mars.

Commercial LEO should be designed to support extended-duration missions of ^**TBD-004**^ length.

ISS should continue to serve as risk reduction testbed and implement the CIPHER study with six-week, six-month and one-year studies to provide necessary long-duration data in microgravity.

This objective will enable evaluation of partial gravity's role in spaceflight adaptations, long-duration physiological mechanisms, and psychological and behavioral adaptations in preparation for a Mars mission.

3.3.2 HEOMD Utilization Goal 2

Advance the operational capabilities required for sustainable lunar operations and the first human missions to Mars, including demonstrating approaches to planetary protection.

3.3.2.1 HEOMD Objective 2.1: Characterization of Local Environmental Conditions (natural and induced)

Relevant program/project/location:

Lunar surface	HLS, LTV, xEVA, future surface assets
Lunar transit and orbit	Gateway, xEVA, Orion, future long-duration orbital habitat
Low-Earth orbital	ISS, xEVA, Commercial LEO

Applicable Investigations – ^**TBD-005**^

3.3.2.2 HEOMD Objective 2.2: Develop, test, and demonstrate planetary protection knowledge; understand environments and pathways for microbial contamination.

Relevant program/project/location:

Lunar surface	HLS, LTV, xEVA, future surface assets
Lunar transit and orbit	Gateway, xEVA, Orion, future long-duration orbital habitat
Low-Earth orbital	ISS, xEVA, Commercial LEO

Applicable investigations:

a. Demonstrate microbial monitoring, control, and treatment technologies for terrestrial and potential extra-terrestrial microbial communities to enable planetary protection on future human missions to Mars.

b. Evaluate natural and artificial transfer pathways and technologies for mitigation of microbial contamination (forward to Mars and backward to humans and the Earth).

c. Demonstrate the collection and return of biological and/or scientific samples, including planetary protection goals to understand the survival and viability of terrestrial microorganisms in extra-terrestrial environments.

3.4 NASA MULTI-DIRECTORATE GOALS AND OBJECTIVES

3.4.1 NASA Multi-directorate Utilization Goal 1

Enable commercial, interagency, and international partnerships to make space exploration more affordable and sustainable, grow new markets, and increase capabilities.

HEOMD missions in LEO, in deep space, and on planetary surfaces support and align with the NASA Strategic Plan (2018) to expand human knowledge through new scientific discoveries, extend human presence deeper into space, explore the Moon for sustainable long-term exploration, address national challenges and catalyze economic growth, and optimize capabilities and operations.

Relevant program/project/location:

Lunar surface	HLS, LTV, future surface assets
Lunar transit and orbit	Gateway, Orion, Space Launch System (SLS), future long-duration orbital habitat
Low-Earth orbital	ISS, Commercial LEO

APPENDIX A
ACRONYMS AND ABBREVIATIONS AND GLOSSARY OF TERMS

A1.0 ACRONYMS AND ABBREVIATIONS

AA	Associate Administrator
AES	Advanced Exploration Systems
AHRCWG	Artemis Human Research Complement Working Group
ALSEP	Apollo Lunar Surface Experiment Packs
AUCP	Artemis Utilization Coordination Panel
BDC	Baseline Data Collection
BPS	Biological and Physical Sciences
CIPHER	Complement of Integrated Protocols for Human Exploration Research
CHP	Crew Health and Performance
CHPIDA	Crew Health and Performance Integrated Data Architecture
CLPS	Commercial Lunar Payload Services
CMV	Co-Manifested Vehicle
CNT	Communication and Navigation
ConOps	Concept of Operations
CTO	Candidate Test Objective
DNA	Deoxyribonucleic Acid
DTE	Direct to Earth
EC	Exploration Capabilities
ECLS	Environmental Control and Life Support
ESD	Exploration Systems Development
EVA	Extravehicular Activity
FOD	Flight Operations Directorate
GNC	Guidance Navigation Control
HALO	Habitation and Logistics Outposts
HEO	Human Exploration and Operations
HEOMD	Human Exploration and Operations Mission Directorate
HLS	Human Landing System
HRP	Human Research Program
IHRCWG	International Human Research Complement Working Group
ISRU	*In situ* Resource Utilization
ISS	International Space Station
IVA	Intravehicular (IV) Activity
LEAG	Lunar Exploration Assessment Group
LEO	Low-Earth Orbit
LER	Lunar Exploration Roadmap
LiDAR	Light Detection and Ranging

LLO	Low-Lunar Orbit
LTV	Lunar Terrain Vehicle
LWIMS	Lunar Water IRSU Measurement Study
NASA	National Aeronautics and Space Administration
NID	NASA Interim Directive
NPD	NASA Policy Directive
NPR	NASA Procedural Requirement
NRHO	Near-Rectilinear Halo Orbit
OCE	Office of the Chief Engineer
PNT	Position, Navigation, and Timing
PPE	Power and Propulsion Element
PR	Pressurized Rover
PRR	Path to Risk Reduction
PSR	Permanently or Persistently Shadowed Region
RM	Reference Mission
ROI	Research Operations and Integrations
SANS	Spaceflight-Associated Neuro-Ocular Syndrome
SCEM	Science Context for Exploration of the Moon
SCLT	Strategic Capability Leadership Team
SCOPE	Strategic Campaign Operations Plan for Exploration
SDT	Science Definition Team
SE&I	Systems Engineering and Integration
SH	Surface Habitat
SLS	Space Launch System
SMD	Science Mission Directorate
STMD	Space Technology Mission Directorate
TBD	To Be Determined
TBR	To Be Resolved
TH	Transit Habitat
UCIG	Utilization Coordination and Integration Group
VISE	Vehicle Interface to Suit Equipment
xEMU	Exploration Extravehicular Mobility Unit
xEVA	Exploration Extravehicular Activity

A2.0 GLOSSARY OF TERMS

Term	Description
Architecture	A set of functional capabilities, their translation into elements, their interrelations, and operations. The architecture enables the

Term	Description
	implementation of various mission scenarios that achieve a set of given goals and objectives.
Autonomy	The ability of a system to achieve goals while operating independently of external control. Autonomy is not the same as artificial intelligence but may make use of artificial intelligence methods. Autonomy is not the same as automation, but often relies on automation as a building block.
Autonomy Technology	Consists of the elements and methods required to build, test, and certify an autonomous system. The purpose of autonomy technology is not primarily about making a system adaptive, intelligent, or "smart," but rather to enable a system to achieve goals while operating independently of external control.
Capability	A technology or process matured to the point where it may be utilized to enable or enhance a mission.
Cis-lunar	Space between Earth and the Moon. Within NASA, cis-lunar typically means the deep space frontier around the Moon, thousands of miles beyond the Moon, or the proving ground of deep space near the Moon.
Increment	The period of time between the end of one crew mission (i.e., crew splashdown) and the end of a second crew mission, including the uncrewed activities and operations that commence during this defined timeframe.
Habitable Environment	The environment that is necessary to sustain the life of the crew and to allow the crew to perform their functions in an efficient manner.
Mission	A major activity required to accomplish an Agency goal or to effectively pursue a scientific, technological, or engineering opportunity directly related to an Agency goal. Mission needs are independent of any particular system or technological solution. (Definition from NPR 7120.5).
Robotic Assets	Anything that can be operated independently of human presence on the lunar surface and in cis lunar space.
System	The combination of elements that function together to produce the capabilities required to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes, and procedures needed for the purpose. An autonomous system may involve any combination of elements (e.g. humans and machines) and is not limited to uncrewed capabilities.
TBD	Used when it is not known what value to be placed in a requirement and there is open work to determine what it should be.
Telerobotics	Remote operation of robotic systems in the space environment in such a way that autonomous systems are not necessarily required (but could be used to enhance) operations.

Term	Description
Utilization	The use of a platform and/or mission to conduct science, research, development, test and evaluation, public outreach, education, and commercialization. Utilization is distinct from the carriers and component systems designed to sustain the mission and health of the crew (which include launch vehicles, transportation vehicles, orbital modules, and space suits) [Carrier and payload definitions per NPR 8705.4].
xEVA Systems	Allows crewmembers to conduct excursions outside a habitable vehicle in order to perform exploration, science, construction, servicing, and repair operations. The elements within the xEVA System include: xEVA Suit (e.g. Exploration Extravehicular Mobility Unit (xEMU)), Vehicle Interface to Suit Equipment (VISE), xEVA Tools, and xEVA Accessories.

APPENDIX B
OPEN WORK

B1.0 TO BE DETERMINED

TABLE B1-1 TO BE DETERMINED ITEMS

TBD	Section	Description
TBD-001	3.2.1.2	STMD to provide life support and human performance technologies
TBD-002	3.2.2.1	STMD to provide example technologies
TBD-003	3.2.2.2	STMD to provide example robotic and autonomy technologies
TBD-004	3.3.1.5	Commercial LEO extended-duration mission length
TBD-005	3.3.2.1	Define applicable investigations
TBD-006	Annex 2	Define 10-year phasing plan
TBD-007	Annex 3	Integrated LEO Utilization Objectives
TBD-008	Annex 4.2 and subs	Define Integrated Artemis Mission Utilization Objectives for subsequent landed missions

B2.0 TO BE RESOLVED

None.

ANNEX-1
CORNERSTONE CAPABILITIES THAT ENABLE MULTIPLE OBJECTIVES

AN1.0 INTRODUCTION

In this annex, NASA has developed integrated, cross-cutting capabilities, defined here as Cornerstone Capabilities (see Table AN1.0-1) that are necessary to achieve the utilization goals and objectives from multiple NASA mission directorates as defined in the main body of HEOMD-006 (Section 3.0). Each Cornerstone Capability is a complex mission operation that enables utilization. The operations are complex because they are dependent on a set of capabilities and functions that are provided across multiple Low-Earth Orbit (LEO) and Artemis systems and cannot be implemented or achieved by a single program or organization. The Cornerstone Capability narratives were developed to illustrate the dependencies between Human Exploration and Operations Mission Directorate (HEOMD) elements and utilization needs to inform the development of HEOMD system requirements and other system implementation activities. These descriptions were predominantly developed through the Utilization Coordination and Integration Group (UCIG), with participation from representatives across HEOMD, Science Mission Directorate (SMD), and Space Technology Mission Directorate (STMD). This set of Cornerstone Capabilities was based on a current understanding of the strategic utilization needs as well as human exploration system architectures (HEOMD-007, Strategic Campaign Operations Plan for Exploration (SCOPE)). However, it is anticipated that this set of Cornerstone Capabilities will evolve as the human exploration systems mature and utilization needs become better defined. Any significant revisions to the referenced documents will be configuration managed using administrative updates as needed.

TABLE AN1.0-1 CORNERSTONE CAPABILITIES

AN1.1 Model Traverse Approaches: Access and perform operations in new terrain, enabling traverse use cases to inform crew and rover mobility, and establish communications and navigation needs
AN1.2 End-to-End Sampling Strategy: End-to-end sampling, curation, analysis and transport strategy, including collection of rocks, regolith, cores, biological/human research samples, physical sciences and *In situ* Resource Utilization (ISRU) samples; includes cold-conditioned sample stowage
AN1.3 Integrated Planetary Protection Strategy: Integrated planetary protection strategy and microbial monitoring across the Artemis program and elements
AN1.4 Extended Missions: Extended duration orbit/surface missions for experiments and technology development (applies to both ISS and Artemis)
AN1.5 Integrated Crew Research: Integrated/coordinated access to human test subjects from pre- to post-flight
AN1.6 Robotic Utilization for HEO Assets: Uncrewed/robotic operations for utilization of HEO assets to support science and technology objectives
AN1.7 Integrated Instrumentation Strategy: *In situ* and remote sensing instrumentation, deployed experiments and measurements, including external instruments, Intravehicular Activity (IVA) science and real time Extravehicular Activity (EVA) measurements
AN1.8 Complex Operations in Cold/Shadowed Regions and Volatile-bearing Terrain: Conducting science investigations and resource utilization in permanently or persistently shadowed regions (PSR)

Each Cornerstone Capability 1) defines its importance and relevance for utilization, and 2) specifies the capability enablers – the systems that are part of NASA's human exploration architecture that will be needed for fulfilling the utilization goals. These descriptions are intended to be used for reference; this is not a requirements document and approval of this annex does not mandate specific requirements. The Cornerstone Capability descriptions can identify requirements for elements and programs that may be later documented in requirements documents, frame enveloping requirements for future utilization systems, be used as inputs to trade studies, identify risks in order to increase situational awareness and safety for longer and more complex operational conditions, and/or inform utilization needs for specific missions (see Figure AN1.0-1). Cornerstone capabilities may be phased in over many missions, and some may not be fully feasible. Each Cornerstone Capability description also documents the most important linked requirements currently in HEOMD-004 (Human Exploration Requirements) to show how the utilization informs the requirements and to provide a reference for requirements that are critical for utilization. Cross-directorate agreements and decisions about planned capabilities and directorate-level requirements are documented in HEOMD-004.

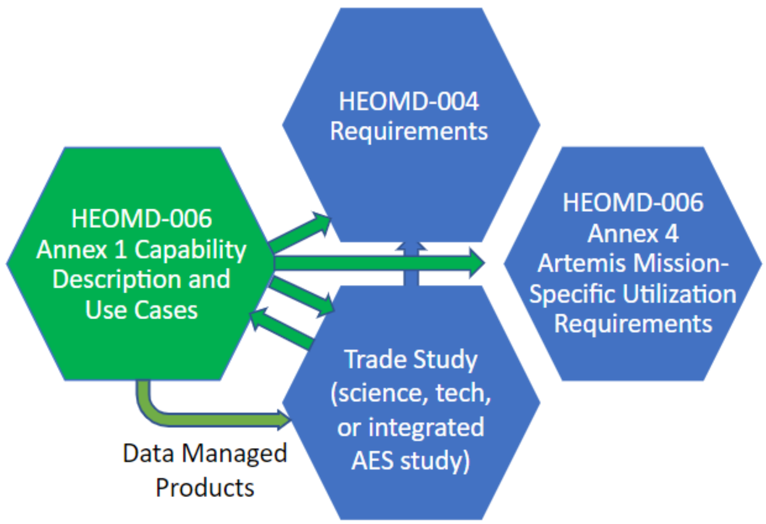

FIGURE AN1.0-1 REQUIREMENT/TRADE STUDY FLOW FROM CORNERSTONE CAPABILITY DESCRIPTIONS

AN1.1 MODEL TRAVERSE APPROACHES

AN1.1.1 Importance

The cornerstone of future human missions to lunar and planetary surfaces is the ability to investigate previously unexplored regions of the Moon and, eventually, interplanetary space and Mars. Artemis human missions provide critical capabilities to access new terrain in the lunar south polar region, with opportunities for profound scientific discovery. Enabling traverses to new terrain is the foundation of human exploration of the Moon and will enable the achievement of numerous compelling, high-priority science objectives. This utilization capability is described in the following scientific community documents:

- *2007 National Research Council Report on the Scientific Context for the Exploration of the Moon*

- *2013-2023 Planetary Science Decadal Survey*
- *Lunar Exploration Roadmap maintained by the NASA Lunar Exploration Analysis Group*
- *Artemis III Science Definition Team (SDT) Report (2020)*

The purpose of this section is to describe various potential lunar surface crew traverse approaches and needs (capability enablers) that are key to meeting scientific goals.

Scientific and exploration activities requiring traverses of human missions and using human mission assets include:

a. *Geologic Characterization*: As NASA explores new terrain, the ability of scientifically trained astronauts to provide detailed geologic descriptions and document their findings will enable a new view of lunar science. This includes geological characterization over a broad, regional scale as enabled by rover mobility and observations from orbit, as well as on a local scale around a lander, rover, habitat, or specific base camp.

b. *Sample Collection and Curation*: The meticulous collection, curation, and return to terrestrial laboratories of lunar samples will unlock a new era of lunar and planetary science (see AN1.2).

c. *Science Instrument and Payload Deployment*: The *in situ* use of both handheld instruments and deployed science payloads at different locations and during traverses on the Moon will provide astronauts and science teams with crucial data, both during an exploration mission and post-crew departure (see AN1.7).

d. *Access to PSRs and cold/shadowed regions that may be volatile-bearing*: Artemis operations in the lunar south polar regions will afford access to cold and shadowed terrain, enabling scientific study of preserved volatiles and surfaces with a unique history of exposure to the solar wind. Operating in these areas introduces operational complexities, including challenging terrain and lighting and thermal environments (see AN1.8).

e. *Resource Identification and Characterization*: Activities to characterize and understand the geology of the lunar south polar region are the foundation for a utilization plan for resources (e.g., sunlight, water, and other volatiles) that could be used to establish a long-term human presence on the lunar surface.

AN1.1.2 Capability Enablers

Traverses designed to explore new and diverse areas of the lunar surface are necessary in order to collect critical science data, to address high-priority Artemis science objectives, to prepare for longer duration Artemis missions in the future, as well as to prepare for the eventual journey to Mars. These traverses, with astronauts as well as robotic explorers, must be carefully planned ahead of time based on all available data from remote sensing and precursor missions, and must also be revised in reaction to discoveries made in real-time. Apollo, Mars rover, and terrestrial analog experiences have demonstrated that flexible execution of pre-planned traverses is essential for achieving the science objectives of the mission. Exploration traverses will depend on and be enabled through the following capabilities and enabling parameters.

Landing Site: Lunar exploration includes both south polar exploration as well as sorties to non-polar locations (See HEOMD-004, HEO-R-9). Such exploration will include highly illuminated regions, partially shadowed regions, and PSRs. Science mission drivers will require access to regions outside the zone of contamination from the lander descent engine(s) plume, diverse geologic areas to allow for access to a variety of materials, a variety of terrains with variable topographic and slope characteristics, and precise targeting of high-priority science targets identified from orbit.

Traverse Distances: Traverses, regardless of what mobility assets are used, will take place on every surface mission in the Artemis Program. The number and duration of each traverse will be dependent on each mission and the program surface architecture, surface asset availability, and the selected landing site and associated science objectives. The expectation is that surface mobility capabilities and traverse complexity will increase throughout the program. Although early missions will be limited to near-field walking traverses, enhanced mobility capabilities will expand access to additional sites of interest, enhancing opportunities to address key utilization objectives. An unpressurized rover will enable access to multiple geologic units and the deployment of remote instrumentation packages at distances of many kilometers from the landing site, and an addition of a Pressurized Rover (PR) will enable access over even longer distances. Accessing these terrains will allow crew to observe first-hand geologic context and collect key samples to address utilization objectives identified above. Traverses will need to be supported by communications assets and Earth-based support teams, and longer traverses may require more communications assets than shorter traverses. Traverse distance requirements from this Section, will be reflected in HEOMD-004, HEO-R-1 and HEO-R-2. The overall distribution of analyzed traverses and distances across landing sites and exploration sites is reflected in TBR Data Books HEOMD-410 and HEOMD-414.

Traverse Styles: There are a variety of traverse styles expected for the Artemis Program. The style that is ultimately executed will depend on science priorities, assets available, landing site, mission duration, and sample return and curation capability, among other factors. Additionally, multiple traverse use cases may be employed in the same mission (e.g., a crewed mission that also includes a robotic explorer or a PR traverse that also includes walking traverses away from the rover).

a. *Walking.* Walking traverses include suited astronauts traversing away from the lander, rover, or habitat. The distance traveled away from the point of departure (e.g., lander, PR) will be limited to the range enabled by the communications and navigation architecture, as well as suit consumables and mobility (and associated contingency scenarios). Instruments and tools intended to be deployed and/or used by crew will have to be transported either directly by crew or on a crew-pulled cart or robotic assistant, as would any samples collected by crew.

b. *Unpressurized Rover(s).* Compared to walking traverses, traverses with unpressurized rovers will enable access to more diverse regions. These rover assets can also carry all the field tools and other equipment that the crew would use on the traverse and all the samples collected during each traverse. The surface mobility vehicle such as Lunar Terrain Vehicle (LTV) is a key part of both crewed and uncrewed use for traverses.

c. *Pressurized Rover.* This traverse style would maximize science return, as it would mean that crews would not have to return to the habitat at the end of each EVA, but could travel increasingly farther away from the habitat, living in the rover for the duration of the traverse rather than the habitat. Like the unpressurized rover, the PR will be able to carry all instruments and tools used by crew on EVA, as well as store and transport samples collected by crew back to the habitat and/or ascent vehicle.

d. *Robotic Explorer.* An Artemis lunar surface traverse could include uncrewed operation with one or more robotic assets (see AN1.6), including surface mobility vehicles such as LTV and small automated rovers, allowing more science to be conducted on the lunar surface in parallel with and complementary to human activities.

Operational functions: Since exploration-based traverses are critical to accomplishing science and other mission objectives, the HEOMD elements must provide the following set of critical operational functions to enable these traverses:

a. *Mobility*: including the use of pressurized and unpressurized vehicles, and other robotic elements (including rovers and mobile crew support systems) to get to the exploration sites of interest for scientific research and technology demonstration.

1. Mobility enables transportation of crew, tools, instruments, samples, etc., beyond what the crew alone can carry and extends the range for exploration.

2. Surface vehicles will serve as mobile science observation platforms that include scientific instruments, cameras, and supplemental lighting. Habitable mobile platforms will also have the added benefit of providing habitation for the crew, rapid-egress EVA capability, and advanced capabilities for the crew to conduct IVA observations and scientific data collection. The mobile science observation function will enable the science support team to assist crew in identifying samples of interest as well as enable broader situational awareness in support of crew and mission safety.

3. Mobility of autonomous or tele-operated robotic assets can also be used for forward reconnaissance of scientific sites of interest in advance of crew arrival or just ahead of the crew for path-planning purposes. Data collected on reconnaissance traverses will streamline collection site selection and traverse planning to optimize crew time spent on EVA and maximize the value of scientific data return.

b. *Navigation*: Guidance, Navigation and Control (GNC) or Position, Navigation, and Timing (PNT): precision targeting and location awareness necessary for precise navigation to specific science targets, which was shown to be difficult in Apollo (e.g., the rim of Cone Crater during Apollo 14). In addition, navigation is an important part of geolocation of where samples are collected, and instruments are deployed. This navigation capability should include GNC or PNT. Vehicle, sample, asset, and logistics tracking and time synchronization are needed for precise positioning and tracking capabilities as they will improve autonomous navigation and proximity operations. At all times during EVA, it is expected to know the location of the EV crew and the path to a safe haven. This path determination may not be possible using visual cues alone due to the terrain and lighting.

c. *Communications*: the ability to transmit data (audio, video, imagery, instrumentation, navigation) between the lunar surface assets (including IV and EV crew and assets like vehicles and satellites) and the support team on Earth with acceptable latency for data collection and analysis; to enable communication and guidance (procedures, contingencies, science direction) from the Flight Control Team and Science Team to the crew; and public outreach.

d. *Data/Telemetry Visualization*: different traverse styles will require different levels of networked capability to enable both the crew and mission support on Earth to view data, procedures, maps, remotely sensed data, etc. These data will also be required by the IV and EV crew and may be portrayed in different formats.

e. *Tools and Payloads*: support for transportation and operation of tools, payloads, hardware, instruments, etc., on the lunar surface which would be more robust with increased downmass and upmass; including logistics for delivery to and deployment on the lunar surface, crew time required to assemble and deploy payloads or operate instruments (including contingency crew time for instrument operations), resources such as power, data, and thermal support, etc. (See AN1.7, Integrated Instrumentation Strategy).

f. *Landing Site Selection*: the ability to land in the proximity of a variety of science targets of interest will maximize the potential for science return. Remote sensing data is critical for landing site selection, verification, traverse design, and tracking crew location while on traverse.

g. *Mission and EVA Duration*: longer duration missions with greater downmass and upmass enable more robust exploration capabilities (demonstrated during the Apollo J-missions). Longer duration EVAs can result in increased distance traveled away from the lander including both suit-only EVAs or surface mobility vehicles such as LTV-enabled EVAs for traversing which in turn results in more samples being collected and a larger volume of exploration data and more samples being collected for *in situ* analyses in a surface laboratory or for return to Earth.

h. *Varied Terrain and Cold/PSR Operations*: high-priority science objectives will be enabled by operations in shadowed terrains and PSRs. Missions with hardware that enable access to these regions will maximize science return (see AN1.6 and AN1.8).

i. *Lighting*: natural and supplemental lighting will be needed for illuminating navigation paths, for enabling science objectives in partially and fully shadowed terrains, and for operating rovers and robotic assets. Supplemental lighting options include suit-mounted, rover-mounted, and portable or astronaut-held lights.

j. Power: power will be needed for traverse assets including suits, tools, payloads, robotic assets, etc.

HEOMD will be the organization responsible for overall management of the “boots on the ground” conducting the exploration traverses that address SMD and STMD objectives. HEOMD will provide the crew and Exploration Extravehicular Activity (xEVA) capability as well as the human mobility assets to execute the traverses, the critical surface support assets such as life support (Human Landing System (HLS), Surface Habitat (SH)), communications, navigation, and the Mission Control support to the crew.

AN1.1.3 Conclusion

Significant science and technology data will be collected through a series of walking, rover, and robotic traverses that will benefit numerous communities. Data enabled by traverses will be used heavily by stakeholders from across SMD, HEOMD, and STMD as well as stakeholders from academia, commercial entities, and international partners to examine the Moon, learn how to operate on the Moon, and prepare for the exploration of Mars. While the style of exploration traverses will vary depending on the mission, each exploration style, when supported by the operational functions listed above, will yield critical science and technology data that will be used for scientific discovery on the Moon and feed forward to preparing for the exploration of Mars in this productive and dynamic new era of planetary surface exploration.
Traverses and mobility represent the most important utilization enabling capabilities, both for early access to compelling exploration locations, and for the ability of the architecture to enable ongoing discovery over a sustained period. Figure AN1.1-1 summarizes, at a high level, each traverse style’s potential for achieving a variety science and technology objectives, based on broad assumptions regarding the constraints imposed on traverses by the hardware systems and architecture as they are currently defined.

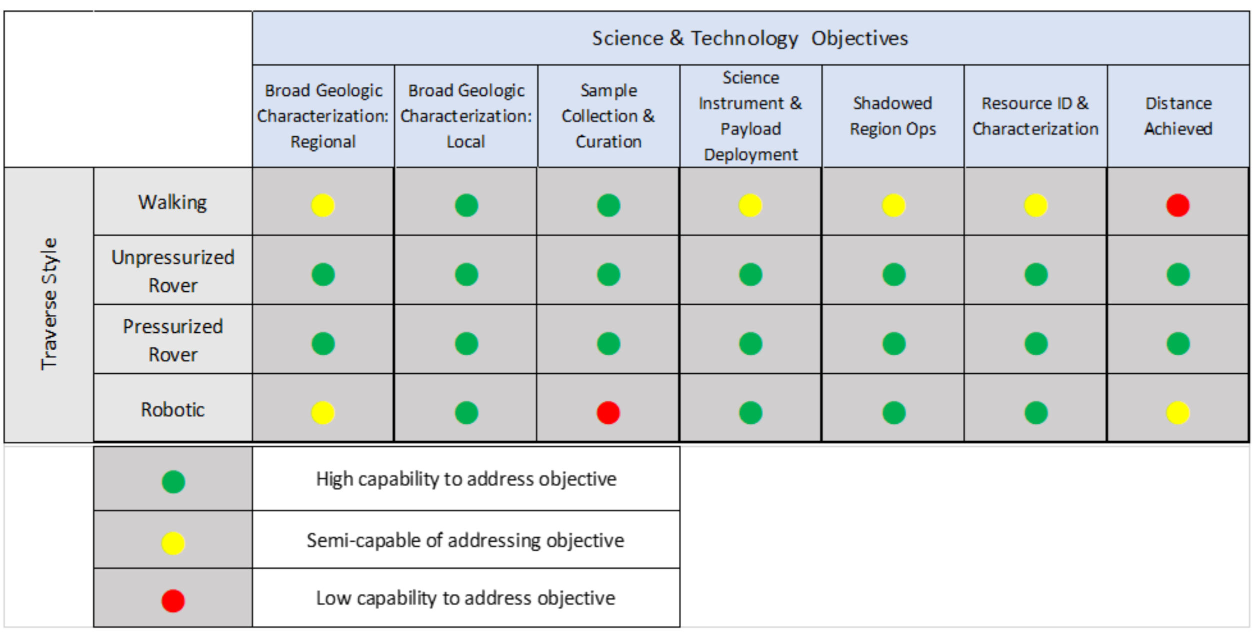

FIGURE AN1.1-1 SUMMARY OF TRAVERSE USE CASES AND THEIR POTENTIAL TO ADDRESS SCIENCE AND TECHNOLOGY OBJECTIVES

TABLE AN1.1-1 TRAVERSE USE CASE CORRELATED REQUIREMENTS, DATA BOOKS, AND/OR TRADE STUDIES

	Requirements (HEOMD-004) or Data Book *denotes products are in process at time of this publication	
AN1.1 MODEL TRAVERSE APPROACHES	HEO-R-6	Lunar Surface Initial EVA Operations
	HEO-R-7	Lunar Surface Sustained EVA Operations
	HEO-R-9	South Pole Lunar Access
	HEO-R-10	Lunar Surface Operational Distance from Originating Habitat
	HEO-R-15*	Crew Location
	HEO-R-25*	Operations in Complex Terrain
	LTV-R-5	LTV Operating Environment
	LTV-R-10	LTV Transport Mass
	LTV-R-11*	LTV Science and Utilization Capability
	CNT-R-1	Lunar Relay Communications Function
	CNT-R-2	Lunar Relay Position Navigation and Timing Function
	CNT-R-11	Real-time Communications Relay Return High Data-Rate (Initial)
	CNT-R-15	Real-time Communications Relay Return High-Rate (Expanded)
	HEOMD-410*	Lunar Traverse Data Book

AN1.2 END-TO-END SAMPLING STRATEGY

AN1.2.1 Importance

The Artemis missions will provide a new opportunity for studying the Moon, the evolution and current state of the solar wind in cislunar space, developing a greater understanding of crew health and performance on deep space missions, and for performing biological and physical science investigations in the unique lunar environment. While *in situ* measurements provide useful information for these critical investigations, sample return leverages the world's state-of-the-art laboratory facilities, enabling a multitude of sensitive analyses that would not be possible with current in-space technologies. In addition, the Apollo samples have demonstrated that with careful and robust sample curation, geologic samples returned to Earth can continue to provide answers to critical science questions decades after they were collected.

The purpose of this section includes defining the types of samples planned to be collected and returned during Artemis missions, the vehicles and other hardware and architecture considerations needed to do so, and the various challenges associated with sample preservation and transport. This section does not include payloads where samples are not returned or their prioritization. This section is to be used as a reference and is not a requirements document.

The *Artemis III SDT Report* (SDT, 2020) describes the SMD science goals of Artemis early missions in detail; the Human Research Program (HRP) has also defined objectives for human research for Artemis missions, including Gateway and lunar surface research. This annex does not include human exploration of Mars and associated sample return, but it will be expanded as new sample return destinations that warrant sample return are identified. This section is intended to be forward-looking, because the technologies developed for lunar sample return will enable sample return from future Mars and other Solar System exploration endeavors.

Several types of samples are planned for collection and return: geology samples, human research samples, cislunar space environment samples, and samples from biological, physical science and ISRU experiments. There may be overlap between the sample types in terms of how they are collected, stored, transported, and studied; these overlaps will support the collaborative use of spacecraft resources, thereby minimizing the overall mass and volume impact for all returned samples.

a. *Geology samples* include materials collected from the lunar surface for the purpose of scientific investigations and ISRU efforts. These samples can take the form of rocks and particles from the surface and subsurface, regolith samples, cores and drive tubes, volatiles trapped in a sampling device, etc. The Apollo Program provided significant experience in documenting, collecting, transporting, and curating lunar samples; Artemis will build upon that experience while incorporating new materials, scientific studies, and novel approaches to collecting and returning lunar samples tailored for volatiles investigations and ISRU technology development.

b. *Human research samples* include biological and other materials collected from astronauts in-flight or non-biological samples that could travel with the crew or be delivered to the lunar vicinity from Earth. Samples from these studies investigate the effects of the deep space hazard environment (e.g., altered gravity, radiation, isolation/confinement, distance from Earth, and hostile/closed environment) on crew health and performance. In-flight crew samples could include blood, urine, fecal, saliva, and body swabs. Non-biological samples could include food and pharmaceuticals. Human research samples will need both ambient and cold stowage. In early Artemis missions, sample return to Earth for analyses will be used with limited *in situ* analysis. For later, longer Artemis missions, the reliance on *in situ* analysis will increase to employ a Mars-forward research strategy. Artemis will build upon experience from previous missions (e.g., the Space Shuttle and the ISS) where human research samples have been collected and returned successfully for decades.

c. *Space environment samples* include regolith samples (overlapping with geologic samples), and samples of impacting particles both at the lunar surface and in lunar orbit. These samples could be used to investigate the history of solar activity in cislunar space as well as to analyze current influxes of solar wind and interplanetary particles in cislunar space. Space environment samples also include hardware and instruments that have been exposed to the surface and space environment.

d. *Samples from biological science experiments* include samples of microorganisms and complex organisms (e.g., plants, frozen rodent parts, or live animals) to support investigations of how various organisms adapt to, and are affected by, the lunar environment. These samples may take the form of bacterial and fungal cultures, vertebrate and invertebrate tissue, live animal and environmental samples, and science payloads (e.g., tissue-on-a-chip) that must be returned to Earth for detailed laboratory analysis. Such samples have a long history of collection and return on prior human spaceflight missions. However, recent advances in biological investigations and analytical capabilities will make it possible to do certain *in situ* analyses and conduct unprecedented biological science in deep space environments.

e. *ISRU and physical science samples* involve three types of samples: 1) pre- and post-processed regolith, 2) intermediate and final gas, liquid, and/or solid products from physical science experiments and ISRU processing, and 3) coupons or hardware associated with physical science experiments, ISRU processing, and exposed materials. Pre- and post-processed regolith allows for full understanding of the ISRU process operation with actual lunar material. Evaluation of products from intermediate and final ISRU processes allows for understanding of the ISRU process performance as well as potential contaminants and constituents not considered or seen with terrestrial simulants before product usage. Coupons and hardware associated with ISRU processing, exposed equipment, and test samples allows for close inspection for better understanding of performance, wear, life, or other physical property effects.

AN1.2.2 Capability Enablers

Artemis utilization sampling will occur during all phases of each crewed mission, including during operations on the lunar surface, in-transit and orbital mission phases, and pre- and post-flight. Sampling tools and sample stowage capabilities will be required on Orion, HLS, Gateway, unpressurized/pressurized rovers, future cargo, SH, and the lunar surface. All these programs and elements must integrate together to enable mission objectives that will change from flight to flight. Pre- and post-flight sampling, sample receiving, and curation will require terrestrial labs and curatorial facilities.

Sample return requires coordination between multiple spacecraft, hardware and stowage types, environmental considerations, and operations constraints. These include:

a. *Mass and Volume:* All samples and sample return hardware must fit within the mass and volume constraints of the vehicles in which they will be transported. While the required mass and volume have been defined for the initial HLS and Orion, the capabilities of these systems may not meet the overall science and technology demand for Initial and Sustained Lunar missions, and additional options and trade studies are needed to enable the return of desired quantities of scientific samples from all Artemis missions.

b. *Contamination Control:* Other sample collection, stowage, and transport requirements for sterility, particulate cleanliness, organic contamination, contamination knowledge, etc., will need to be defined and balanced between the various sample types. Safety considerations for the samples will also need to be defined and addressed, such as for samples in preservatives or that could release volatiles. Finally, overlapping engineering requirements for the various sample types should be identified and their impacts to the mission addressed.

c. *Conditioned Stowage:* Many of the returned samples will be temperature-sensitive, requiring conditioning of some kind (including cryogenic temperatures) to preserve them for analysis on Earth. Different types of samples will need different stowage temperatures to preserve samples for analysis on Earth, as indicated in Table AN1.2-1. Given these different stowage temperature needs, separate or complementary cold stowage will be needed to accommodate the sample requirements. Limited mass and volume constraints will impact the number and types of samples with differing cold stowage requirements on an individual mission or across different missions. The associated power and data requirements for conditioned stowage should be coordinated between all vehicles. Other parameters may be of consideration in addition to temperature such as humidity, vibration, pressure, light sensitivity, etc.

d. *Sample Transport and Timeline:* Some samples will have time-sensitive measurements or analyses that will need to be made at specific points in the mission schedule (within a time range) before launch, after launch, in flight, after sample collection, or immediately after Earth return. Additionally, some samples will have specific stowage requirements that must be implemented quickly after sample collection to ensure sample preservation (e.g., human research biological samples and conditioned stowage samples, particularly geologic samples collected from cold PSRs or shadowed terrain). The time constraints for collecting, analyzing, stowing, and returning these samples must be included when crafting mission timelines including Flight Plan development process.

e. *Operations Considerations:* All the samples described in this section will require some degree of crew involvement in their collection, stowage, transport, and return. Adequate crew training and mission time will need to be allocated to ensure the samples are appropriately collected and stowed.

TABLE AN1.2-1 EXAMPLES OF CONDITIONED SAMPLES AND STOWAGE TEMPERATURES

Sample Type	Description	Sample Stowage Temperature Range (°C)*
Geological	Cores, volatiles from cold traps or PSRs	-85 to –233** (location and sample-dependent)
Biological	Both preserved and unpreserved biological specimens and reagents	+4 (in fixatives), -20 (short-term storage), and -80 to -230 (indefinite storage)
Human Research	Blood, urine, fecal, saliva, body swabs, food, pharmaceuticals, reagents	Ambient but insulated, +4 (e.g., reagents), -20 (e.g., purified biological molecules), -80 (e.g., tissues, cells, whole organisms), TBD (e.g., food and pharmaceutical samples)

*Temperatures need to remain as consistent as possible until Earth return; temperature variations should be minimized to prevent sample degradation.

**These values are based on the estimated sublimation temperatures of volatiles that have been detected on the Moon. The exact temperature stowage/storage requirements for lunar polar geologic samples will be determined empirically via laboratory testing (and documented in TBR HEOMD-413 Utilization Sample Return Conditioned Transportation Needs for Artemis Capabilities).

The sample return capability is predicated on several assumptions, including the capability of the major Artemis spacecraft for the delivery of sample return hardware from Earth, and the return of samples back to Earth at mission completion. The spacecraft expected to transport or carry samples include the HLS, the Gateway, logistics and future cargo return vehicles, and the

Orion capsule. Additionally, key utilization objectives require the ability of conditioned stowage; the operations concepts and required systems are still being defined. Conditioned stowage requires developing freezers that will need mass, volume, power, and potentially data from the spacecraft where it will be operated. Some of the potential temperature requirements for samples collected in shadowed regions are much colder than sample return conditions previously conducted in human spaceflight and thus may require technology development and phased implementation into the architecture.

Sample conditioning and return cannot be successfully completed by any mission directorate working alone. To maximize the effectiveness of the returned samples, the concept of operations (ConOps) for sample return must be well coordinated across Artemis elements as well as between mission planners and utilization stakeholders. The ConOps includes preflight requirements, transport to and from the lunar vicinity, lunar orbital and surface operations, and sample recovery/distribution. The planned scientific or technology investigations, necessary hardware, spacecraft and associated mass constraints, and crewmember availability/ involvement are necessary to define in the mission planning phases. In particular, requirements for sample collection and transport may include cleanliness, sterility, physical isolation/sealed containers, maintenance of vacuum, temperature conditioning, and timing of events.

AN1.2.3 Conclusion

Sample return is a multi-directorate effort, requiring comprehensive mission planning, hardware development, and significant cross-program integration for the development of sample collection and transportation hardware, operations, and implementation (HEOMD); the expertise of the scientific community for defining sample collection requirements and operations requirements (SMD and HEOMD/ HRP); and the development and implementation of new technologies to meet the challenges of modern science and spaceflight (STMD and HEOMD/HRP). This end-to-end Artemis sampling strategy applies to geology, human research, space biology, space environment, physical science, ISRU, and materials samples. While NASA has experience in collecting all the sample types identified, the Artemis missions will be the first time all those samples will be returned at once from a deep space environment. Sample return will accelerate NASA's ability to return unique samples by applying cutting-edge science to the design of new technologies, and to the development of state-of-the-art payloads.

TABLE AN1.2-2 ARTEMIS SAMPLING CORRELATED REQUIREMENTS, DATA BOOKS, AND/OR TRADE STUDIES

	Requirements (HEOMD-004), Data Book or Trade Study *denotes products are in process at time of this publication	
AN1.2 END-TO-END SAMPLING STRATEGY	HEO-R-13	Utilization Payload Return from the Lunar Surface
	HEO-R-14*	Conditioned Sample Return from the Lunar Surface
	HEO-R-23*	Habitable Asset Delivery to the Lunar Surface
	HEO-R-24*	Crew Access for Data and Sample Collection
	Gateway-R-8	Gateway Science Experiment and Technology Demonstration Accommodation
	HLS-R-6	HLS-Initial Utilization Delivery
	HEOMD-413*	Utilization Sample Return Conditioned Transportation Needs for Artemis Capabilities

AN1.3 INTEGRATED PLANETARY PROTECTION RESEARCH AND TECHNOLOGY STRATEGY

AN1.3.1 Importance

Planetary Protection is the process of limiting terrestrial biological cross-contamination to biologically sensitive planetary bodies. Planetary bodies are categorized based on the likelihood of current or past life, and the potential severity of cross-contamination between those bodies and the Earth. Forward contamination is the arm of planetary protection that addresses contamination brought to other bodies by terrestrial hardware or humans. Back contamination addresses potential terrestrial contamination by extraterrestrial biota, which could occur via sample return or crew exposure. In addition, to enable future Mars science, pristine sample acquisition is a key enabling technology that can be demonstrated at the Moon. The Moon has two planetary protection categorization for surface missions, as described in NPR 8715.24. Polar regions (that include PSRs) are categorized as IIb, where they are "of significant interest relative to the process of chemical evolution" in the Solar System but with "only a remote chance that contamination by spacecraft could compromise future investigations." Reporting of organic materials, including propellant volatiles introduced into the lunar environment is warranted. The rest of the lunar surface is categorized as IIa, and is of lesser interest for understanding the process of chemical evolution. Only reporting of propellant volatiles (that would be cold trapped in PSRs) is warranted for IIa missions.

NID 8715.129 states that: "Future missions to Mars shall prevent potential harmful contamination of Earth from Martian microbes that may come from Mars, should they exist". Mars-specific planetary protection objectives are captured in HEOMD-006 HEOMD Utilization Goal 2: "Advance the operational capabilities required for sustainable lunar operations and the first human missions to Mars, including demonstrating approaches to planetary protection" and HEOMD Objective 2.2: "Develop, test and demonstrate *planetary protection* knowledge; understand environments and pathways for microbial contamination." While the Moon does not have specific microbial mitigation requirements, testing and demonstration of the technologies to monitor and mitigate microbial contamination during human missions on the Moon can enable those capabilities on Mars.

NASA has had a program of planetary protection since before the Apollo era, and NPD 8020.7 and NPR 8715.24 lay out policy and requirements for missions traveling beyond communication and navigation (CNT). Human missions to Mars are far more complex and will require development of a new end-to-end NASA planetary protection approach. The NID 8715.129 for human missions to Mars lays out NASA's pathway for filling the knowledge and capability gaps prior to the development of specific mission requirements.

The coordination activity within NASA for developing a roadmap to enable planetary protection on human missions to Mars included participants principally from HEOMD, Office of Planetary Protection, and SMD. The use cases for planetary protection were identified in part through a broader road-mapping activity to evolve NASA planetary protection requirements and goals from the existing robotic Mars exploration paradigm to a new human Mars exploration paradigm. The origins of the current HEOMD roadmap for planetary protection stem from a series of Committee on Space Research-coordinated interdisciplinary meetings. These have now been integrated as capability gaps in the Moon-to-Mars Program, and subsequently into multi-directorate roadmaps. The roadmaps identify timelines, destinations, and scope for each task in order to reach the point where "Acceptable Levels of Microbial/Organic Releases from Humans and Support Systems" can be determined for the first crewed mission to Mars. Understanding the risks of forward and backward contamination for a future human mission to Mars and validating engineering approaches to planetary protection on those missions are both important areas of research. Studies on ISS and Artemis platforms can help to close knowledge and capability gaps for planetary protection.

AN1.3.2 Capability Enablers

The Planetary Protection Roadmap identifies three use cases:

a. *A capability to monitor microbial contamination*. NASA knows that microorganisms are ubiquitous in crewed systems, with a changing population over time, both in terms of the abundance and occurrence of different microbial species. Microbial monitoring technology has been developed over time for crew health and spacecraft environmental monitoring purposes. This work needs to be further expanded to address planetary protection needs to demonstrate the ability to detect changes in the spacecraft microbiome resulting from exposure to the Martian environment and/or Martian microorganisms to inform planetary protection decision-making during the human exploration of Mars.

b. *An ability to be able to understand and track microbial growth and contamination*. The occurrence and fate of terrestrial microbiology in the environments of spacecraft exposed to deep space and Mars need to be understood to manage risks of forward and backward contamination.

c. *Ability to mitigate microbial contamination as it is identified or anticipated*. Capabilities to process elements of hardware (either by disinfection or sterilization processes) and/or to be able to isolate contaminated material from cleaner environments by isolation or containment is critical to developing and demonstrating the ability to avoid forward and backward contamination, as well as demonstrating pristine sample acquisition, during missions to Mars.

Each of these three capabilities have clear opportunities to be tested and verified by precursor missions in the cislunar environment, and the use cases are identified in NASA's current Planetary Protection Roadmap, and will be further developed and described in future iterations of the roadmap.

This research will be conducted on the ground in research laboratories or in ground analog studies. In addition, ISS, Gateway, EVA suits and lunar surface systems will be used as analog environments to demonstrate microbial monitoring needed for planetary protection activities on a Mars mission.

TABLE AN1.3-1 PLANETARY PROTECTION CORRELATED REQUIREMENTS, DATA BOOKS, AND/OR TRADE STUDIES

	Requirements (HEOMD-004, NPR, NID) *denotes products are in process at time of this publication	
AN1.3 PLANET. PROTECT. STRATEGY	HEO-R-22	EVA Suit Accommodation of Artemis Base Camp Habitable Elements
	NPR-8715.24	Planetary Protection Provisions for Robotic Extraterrestrial Missions
	NID-8715.129	Biological Planetary Protection for Human Missions to Mars

AN1.3.3 Conclusion

The stakeholders for biological planetary protection include a broad range of scientists, medical professionals, resource developers, technologists, and government agencies. Scientists in disciplines such as astrobiology, planetary sciences, microbiology, geomicrobiology, and planetary protection sciences want to study if there is or was life on Mars and want to minimize contamination from Earth microbes. Future explorers are also interested in biological planetary protection as they would need sterile water for ISRU and/or the generation of products such as fuel with local resources. Technologists are interested because systems may degrade due to contamination by microbes and need to be robust to or tolerant of microbial growth (e.g., biofilms). Next, astronauts and their support teams are interested in planetary protection because they want to maintain their health after possible exposure to microbes in Marian material. Further, NASA wants to meet obligations in regard to preventing harm to the environment of the Earth. Finally, multiple other government agencies are interested stakeholders as it impacts their areas of responsibility on behalf of the public and as described in the recently (2020) issued *National Strategy for Planetary Protection*.

The expected outcome of planetary protection will be an evaluation of natural and artificial microbial contamination transfer pathways and to develop technologies for mitigation of such microbial contamination (forward to Mars and backward to humans and the Earth). This includes end-to-end technologies from microbial monitoring, microbial reduction, crew quarantine protocols and breaking the chain of contact between planetary bodies of interest (e.g., Mars) and the Earth. In addition, the planetary protection development activities need to demonstrate the collection and return of pristine biological and/or other scientific samples for the goal of understanding the survival and viability of terrestrial and extra-terrestrial microorganisms in the environment of Mars, deep space, and Earth.

The planetary protection technology development outlined here is essential for development of Planetary Protection policy and requirements for crewed missions at the Agency-level. Timely flow down of Agency-level planetary protection capabilities and requirements will allow their adoption into spacecraft design and operations requirements for the first crewed Mars mission.

AN1.4 EXTENDED MISSIONS

AN1.4.1 Importance

One of the most significant differences between our current human spaceflight missions and the expected Mars mission architectures are the durations over which humans live and work in space environments. This section describes the durations needed to define and ameliorate crew health and performance risks for the first mission to Mars. Three types of mission analogs are needed at appropriate durations: (1) ISS missions as an analog for microgravity transit to Mars, (2) Artemis surface missions as analogs for partial gravity and deep space radiation, and (3) integrated Artemis missions with extended lunar orbit stays combined with surface operations as validation analogs for Mars missions.

The Sustained Lunar Presence segment and multi-purpose development of Artemis elements in HEOMD-007 make use of appropriate mission durations an important enabler of human risk reduction research, countermeasure, and technology demonstration. The overall approach to Human Research is documented in HRP's *Human Research Roadmap,* based on risk assessments maintained by the Human Systems Risk Board under the Health and Medical Technical Authority. *Mars Mission Duration Guidance for Human Risk Assessment and Research Planning Purposes* was documented in HEO-DM-1002. When transportation capabilities are being developed, notification of intent to conduct long duration missions may be needed before such missions become part of the contracted requirements. *Planning guidance for Artemis Mission Durations as Testbeds to Reduce Risks for Human Missions to Mars* was documented in HEO-DM-1004 and in the text of HEOMD-004 to provide this early notification for Artemis programs.

The following summarizes the ways that utilization stakeholders will benefit from executing a small number of Extended Missions on ISS and Artemis.

a. *Test Earth-independent Integrated Operations:* Simulate and test Mars-like flight operations, including crew autonomy, training, communication delay, exploration mission control, and the deep space network. Simulate inclement space weather situational awareness and preparedness.

b. *Test Earth-independent Medical Operations:* Simulate and test Mars-like crew monitoring of their health status, care and nutrition needs and responding to simulated medical contingencies over communication delay.

c. *Test Psychological Countermeasures in Isolation/Confinement Analog*: Test Mars-like psychological countermeasures under isolation/confinement conditions such as smaller habitable volumes, longer mission durations, and crew size/composition factors.

d. *Test Long-duration Deep Space Physiological Countermeasures:* Test physiological countermeasures required for Mars in high-fidelity space hazard environments.

e. *Test Environmental Control & Life Support (ECLS), Food, Space Weather Environmental Warning Systems, and Autonomy in Flight Analogs*: Test systems in the spaceflight environment to validate ground results.

f. *Test Post-landing Surface Fitness in Flight Analogs:* Test crew that have adapted to the microgravity environment over long-duration spaceflight after landing and while transitioning to the partial gravity lunar environment and one-g Earth environment.

g. *Test Mars Science & Traverse Operations Transit and Surface Missions in Lunar Analog*: Allow the crew to conduct multi-Earth-day lunar traverses, science experiments and instrument deployments, and mission logistics using communication delays to simulate science activities in a Mars mission scenario.

h. *Conduct Repeatable Science Experiments for Lunar Traverse and Laboratory Investigations*: Enable the crew to make repeated EVAs to a single station of high geologic complexity, to collect additional sets of data and samples for comparative analysis, and conduct iterative experiments to verify and validate data, findings, conclusions, and models. Also, crew could perform extended-mission sample triage or down-select using analytical equipment in a surface laboratory.

i. *Conduct In situ Utilization*: Enable *in situ* utilization such as analysis of biomedical samples on-board Gateway, laboratory (geology, biology, biomedical, and physical) studies in the SH, field science (sample collection, mapping, and documentation), crew-tended experiments (rather than those that do not need crew intervention), lunar day/night cycle observation, and ISRU. The highly trained crew would have additional time and become more involved in the science investigations, allowing NASA to verify science autonomy and assess overall performance (for non-surface samples). Additionally, the crew would have more time for training, education, and outreach activities.

j. *Conduct Science with Expanded Capabil*ity: Enable expanded science capabilities such as more facility instruments, robust and long-duration cold-stowage, trained scientist crew, in-mission training classes, long-duration science experiments and monitoring on the Moon with possibility of re-supply, experiments over multiple lunar day/night cycles, and follow-on and continuity studies based on data and findings from preceding studies.

AN1.4.2 Capability Enablers

Extended missions have increased crewed durations, and by mission, they are defined as:

a. *ISS:* Six-month and one-year (e.g., Complement of Integrated Protocols for Human Exploration Research – CIPHER).

b. *Commercial LEO:* Greater than 45 Earth days and up to one year.

c. *Artemis:* Refer to extended reference mission (RM) table AN1.4-1. (Note: these RMs will be assessed by the human system risk board and findings will build on preceding mission data analysis).

For HEOMD, extended missions enable Mars risk-reduction in high-fidelity environments with relevant durations that cannot be accomplished with shorter missions or on the Earth. The rationale for the Artemis RM parameters are the following:

a. *Research and Development Testbed*

1. The 30-60 Earth day surface duration allows for evaluation of long-duration physiological mechanisms.

2. Minimal return to Earth time allows evaluation of 1/6 g role in adaptations.

b. *Applied Risk-Reduction Testbed*

1. Per existing data, the standard ISS mission duration applied to missions in cislunar orbit prior to lunar surface will be optimal (Human System risk examples: Sensorimotor, Spaceflight-Associated Neuro-Ocular Syndrome – SANS).

2. The 30-60 Earth day lunar surface mission duration is the same as the current Mars Reference Mission (Human System risk examples: Altered Immune, Team Performance) and allows for evaluation of long-duration physiological mechanisms.

3. The minimal return to Earth time allows evaluation of 1/6 g role in adaptations.

4. The larger “n” (number of crew) allows for meaningful data outcomes.

c. *Risk-Reduction Integrated System Validation*

1. All mission segment durations are the same as current Mars RM durations (HEO-DM-1004) to validate system requirements, such as training, countermeasures, and medical, prior to the actual Mars mission.

2. If results were unexpected, then NASA could assess risk, re-design, or conduct additional testing and analysis prior to the actual Mars mission.

3. Larger “n” allows for meaningful data outcomes.

Extended missions will help both HEOMD and SMD achieve the NASA utilization objectives outlined in HEOMD-006 and the NASA *Artemis Plan*.

For SMD, extended missions with durations of 45-360+ Earth days enable achievement of science objectives with greater iterations of scientific inquiry and investigation (e.g., repeated, and follow-on studies) than those achievable during short missions.

Extended Missions will require cross-platform coordination across Earth (pre/post-flight and experiment controls), LEO, cislunar, deep space, and lunar surface locations.

The ISS and Commercial LEO Extended Missions will occur in the 2020s and 2030s and include pre-flight, inflight, and post-landing mission phases. Artemis Extended missions are expected to occur in the 2030s (HEO-DM-1004). The overall development of duration-based experience is shown in Figure AN1.4-1.

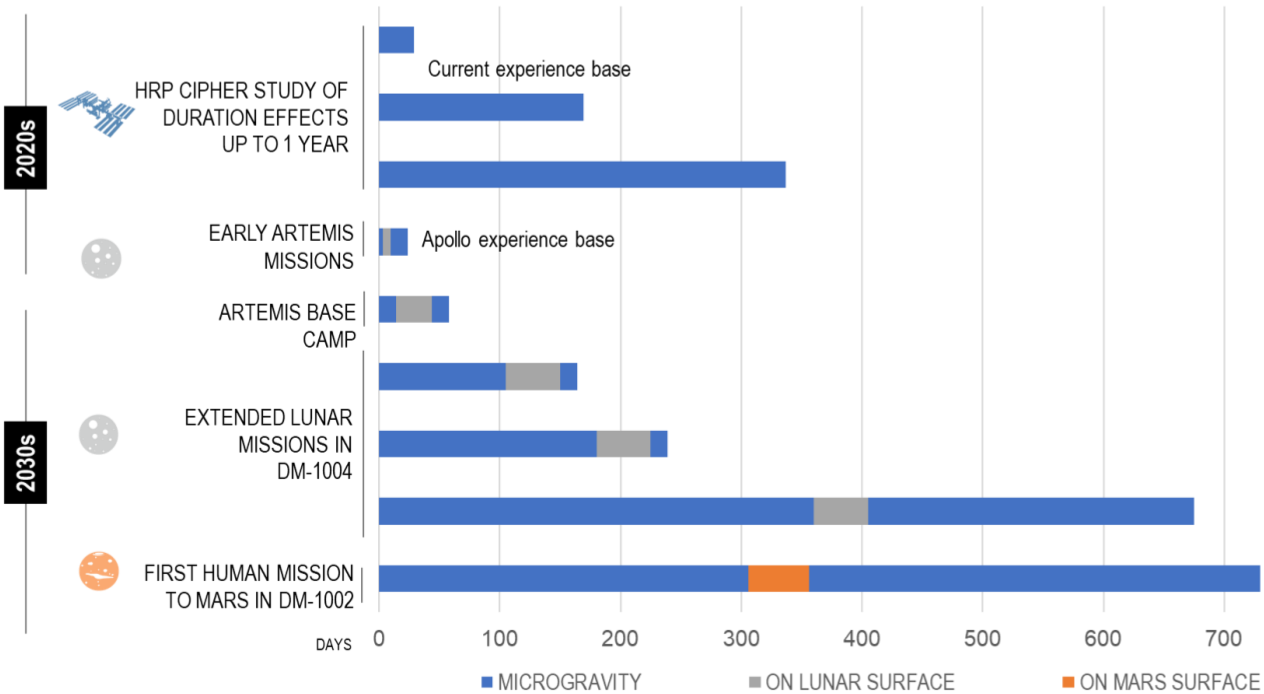

FIGURE AN1.4-1 LEVERAGING INCREASING MISSION DURATIONS ON ISS AND AT THE MOON TO MITIGATE HUMAN SYSTEMS RISKS FOR MARS

TABLE AN1.4-1 ARTEMIS EXTENDED MISSION DURATIONS AND SUBJECT NEEDS

Mission Parameter	**Artemis Extended Duration Missions**		
	Research and Development Testbed	Applied Risk-Reduction Testbed	Risk-Reduction Integrated-System Validation
Time in microgravity pre-lunar surface	45-105 Earth days, 75 Earth days minimum preferred	120-180 Earth days	360 Earth days
Time on lunar surface	30-60 Earth days	30-60 Earth days	30-60 Earth days
Time in microgravity post-lunar surface	11-14 Earth days	11-14 Earth days	270 Earth days (TBD extended duration microgravity environment)
Total crew sample size (n)	4-10 subjects	10-12 subjects, dependent on completion of CIPHER 1-year subjects	10-12 subjects, 4 subjects may be acceptable if Applied Risk-Reduction Testbed were implemented

TABLE AN1.4-2 EXTENDED MISSION USE CASE MAPPING TO HEOMD MISSION

Use Case Short Name	**Mission**		
	ISS	Commercial LEO	Artemis
Earth-Independent Integrated Operations	x	x	x
Earth-Independent Medical Operations	x	x	x
Psychological Isolation/ Confinement Analog		x	x
Physiological Countermeasure Analog	x	x	x
ECLS, Food, and Autonomy Analog	x	x	x
Post-landing Surface Fitness Analog	x	x	x
Mars Science and Traverse Operations			x
Repeatable Lunar Science			x
In situ Science	x	x	x
Expanded Science	x	x	x
CIPHER	x		

Extended missions using the HEOMD platforms enables HEOMD to mature and test human spaceflight systems in the relevant environment over durations representative of those for a Mars mission. Additionally, HEOMD will provide the platform architecture, logistics, and operations for achieving utilization objectives. Finally, HEOMD will provide implementation strategic/tactical leadership, forum, and capabilities for integrating diverse utilization needs across NASA Divisions and with external NASA entities to achieve mission implementation objectives and goals.

AN1.4.3 Conclusion

Extended missions will involve many stakeholders with a variety of objectives and complex relationships. HEOMD will execute safe and successful LEO and lunar missions and prepare for Mars missions. The Office of the Chief Health & Medical Officer will provide crew health and performance standards and assess technical implementation and human system risk mitigation strategies. The Office of the Chief Engineer (OCE) will provide standards and assess technical implementation. The Office of Safety and Mission Assurance will provide safety and mission assurance standards and assess technical implementation and mission safety and assurance strategies. The STMD will perform technology development and infusion for living in space and exploring new destinations. SMD and the scientific community will achieve science objectives articulated in various documents (e.g., the *Artemis Plan, Artemis III SDT Report*, Gateway Utilization 15-Year Outlook, SMD priorities, various Decadal Surveys). Commercial partners and providers may provide some of the needed systems; other government agencies and international partners may be collaborators. Extended missions will provide venues for public participation through education and outreach.

Extended missions are critical to achieving all the advancement of human exploration capabilities and reduction of human systems risks to enable human missions to Mars as defined in HEOMD-007 and are critical in providing tests beds for: 1) risk mitigation strategies validated in a high-fidelity environment prior to extended-duration Mars missions, and 2) scientific knowledge for both fundamental discovery and exploration benefit.

Extended missions are critical pathfinders to test long duration spaceflight impacts on the crew. Using the variety of platforms and space environments provided by ISS, commercial LEO, and the Artemis Program, extended missions enable increased understanding and risk reduction for future human missions to Mars.

TABLE AN1.4-3 EXTENDED MISSION CORRELATED REQUIREMENTS, DATA BOOKS, AND/OR TRADE STUDIES

	Requirements (HEOMD-004)	
AN1.4 EXTENDED MISSIONS	HEO-R-8	Lunar Systems Operations and Interfaces
	HEO-R-17	Crewed In-Space Duration
	HEO-R-19	Crewed Lunar Mission Opportunities
	HEO-R-20	Artemis Base Camp Crew Size

AN1.5 INTEGRATED CREW RESEARCH

AN1.5.1 Importance

Understanding the effects of spaceflight on humans is essential as NASA continues its journey to Mars. The Artemis Program provides an unprecedented opportunity to utilize various platforms – Orion, Gateway, HLS, lunar surface – to advance our knowledge of how to support safe, productive human space travel beyond the relative comfort and safety of LEO. The purpose of this section is to define variables that enable the access to human test subjects, the locations for baseline data collections/training required by human research, and how to best enable the access to human test subjects.

Currently, only a small number of select people travel into space. Because of this, they are a rare and precious resource with respect to availability of human subjects for research. To utilize them to their full potential for advancing human spaceflight, NASA will coordinate and integrate the access to these human subjects to maximize science yield from the research. It is also required that the NASA Institutional Review Board review and approve all human research complements for US astronauts to ensure the crew are being treated in an ethical, safe, and equitable manner.

AN1.5.2 Capability Enablers

Coordinating across all the human research, regardless of agency or organizational sponsorship, is necessary to ensure that NASA is not hindering one set of experiment objectives by collecting data or executing research from a different experiment. For example, without an integration function, it could be possible for a crewmember to consent to a gut microbiome experiment and its role in the immune system and consent to participate in an experiment that requires the crewmember to ingest a certain probiotic. The second experiment would certainly affect the outcome of the first experiment and may confound the results so much that the two experiments are mutually exclusive. There is also the possibility that experiments with similar requirements could share data to gain operational efficiencies and maximize research return. The potential for conflicting research and opportunities for efficiencies increases across the many platforms and environments that are encompassed in the Artemis architecture. ISS best practices for providing robust human research capabilities should be applied within the Artemis structure to enable similar capabilities.

This integration and coordination of human research has been ongoing for the ISS for many years and has been successful by utilizing an ISS program chartered, international working group known as the International Human Research Complement Working Group (IHRCWG). The IHRCWG is responsible for the development of mission and crew-specific human research complement scenarios as part of the ISS research planning process. The development of these complement scenarios is primarily driven by limited crew time in the first week after landing when crewmembers return from ISS. The IHRCWG also serves as a forum to identify inherent scientific conflicts and/or efficiencies between human research experiments as well as those related to scheduling of sessions pre-, in-, and post-flight or other limited human resources (e.g., blood volumes). If any conflicts are identified when developing complement scenarios, proposals are developed and evaluated for possible solutions.

Crewmembers participate in an Informed Consent Briefing where they are briefed on all human research experiments that are available to them for participation. After the briefings, they can indicate which experiments they are willing to volunteer for as research subjects. The IHRCWG is then responsible for developing recommendations for the complement of research that best fits each individual crewmember. Complement recommendations consider the crewmember's willingness to participate in the experiments, the science priorities of the experiment's sponsor, and any interests that the crewmember has expressed (if any).

A similar working group for Artemis will be critical to ensure that the use of any crewmember's time and efforts in volunteering for human research during Artemis missions is maximized. For the intent of this document, this similar working group function will be referred to as the Artemis Human Research Complement Working Group (AHRCWG).

Integrated and coordinated research on human subjects will occur on all NASA human spaceflight platforms, as well as terrestrial facilities and laboratories.

The following personnel are essential in integrating/coordinating the access to human subjects:

a. *Crewmembers*: As the test subjects, their consent is required to participate in an experiment. Experiment participation is voluntary and not guaranteed.

b. *Crew Office and Flight Operations Directorate (FOD)*: Several factors influence the timing of crew assignments by FOD; primarily flight eligibility and core mission training. In order to enable access to the crewmembers, the crew office is responsible for ensuring that mission crewmembers are assigned in a reasonable amount of time to complete all preflight training and baseline data collection required for human research, in addition to their mission training. The crew office is also responsible for scheduling crewmember post-flight testing that needs to occur beyond 6 months post-landing because by this time the crewmembers are no longer scheduled by NASA's FOD. FOD is responsible for scheduling of training and preflight baseline data collection (BDC) for the crewmembers as well as some post-flight BDC from landing +2 weeks through 6 months.

c. *Flight Surgeons*: Crew flight surgeons are responsible for the overall health and safety of the crew and accompany the crew to a majority of the pre- and post-flight baseline data collection sessions. They have the ability and authority to stop participation of the crewmember in an experiment in the interest of crew health and safety.

d. *Research Sponsors*: All research sponsors (including organizations within NASA) and international partners, when appropriate mechanisms or agreements are in place, must agree to support/fund an experiment for the duration and provide the pre- and post-flight testing requirements to the crew schedulers [in FOD and HRP/Research Operations and Integrations Element (ROI)] and the in-flight research requirements to the appropriate program (depending on platform and process) for scheduling with the crewmember.

e. *AHRCWG members*: Members of this working group would be responsible for providing research requirements, constraints, and any other necessary information for complement development and for representing experiment interests to the working group.

f. *HRP/ROI*: Responsible for working with the Medical Operations team to integrate human research activities with medical operations (when appropriate) and in scheduling the first two weeks of post-flight testing for all crew for all experiments that require testing in this timeframe. Also responsible for providing the HRP research requirements to FOD for pre- and post-flight testing as well as the in-flight research requirements to the appropriate program (depending on platform and TBD process) for scheduling with the crewmember.

g. *Artemis Mission Research Planners (Orion, Gateway, lunar surface, other)*: Responsible, along with FOD, for scheduling human research data/sample collection sessions during inflight mission.

h. *Mission Operations and Integration*: Responsible, along with FOD, for integration and execution of crew timelines and management of real time or near real time science data.

The basic process outlined below is important to obtain the access to the crewmember and to ensure that NASA maximizes use of the resource they provide. The description is at a very high level and task based; specific processes and timing will be required in order to accomplish the tasks.

All human research sponsor organizations need to share information about their proposed experiments with all other human research sponsor organizations in order to identify possible conflicts between experiments. Opportunities for data or sample sharing can also be identified that can be implemented if experiments are performed by the same crewmember. This data should include, but not be limited to, the following information:

a. Experiment Summary

b. Operational Summary

c. Pre-/Post-flight BDC session information

d. In-flight data collection session information

e. Sample and measurement information

f. Hardware and software required for pre-/in-/post-flight data collections

g. Any training requirements needed for the crewmember to participate in the experiment

The above information will ideally provide enough information for all sponsors to review other sponsors' proposed experiments and identify any conflicts in data collection methods, timeframes, or any other conflicting issues between experiments. Ideally, this would occur ~18 months prior to launch. Coordination of training requirements to meet their operational objectives will occur with NASA FOD as the responsible body for integrating the Artemis Crew Training Plans. To meet a 2-year Artemis training template, identification of training requirements would ideally occur prior to L-18 months unless they can be accomplished via Computer-Based, or Onboard Training.

HEO's involvement is essential because integrated research on crew includes multi-platform considerations and challenges. Human research is dependent on human participation and often, the measures or samples to be collected are time-based on the crewmember's flight day. Artemis missions will be different from ISS missions in that the crew could spend several Earth days on transfer vehicles to and from the various platforms for exploration. Artemis crews may have to perform data or sample collection upon landing on the lunar surface without help from ground personnel like they have when landing on Earth. In some exploration scenarios, the crew may have spent several weeks or months in microgravity and will experience some deconditioning that may affect their ability to perform these collections without physical assistance from non-deconditioned personnel (i.e., ground personnel supporting current ISS landings). Additionally, some experiments could require data collection not only on Earth for the pre- and post-flight BDC, but also on the Orion vehicle during transport to/from Gateway or lunar orbit, as well as on HLS to/from the lunar surface and then on the lunar surface itself. This could present a unique situation where the experiment will span across multiple Programs for coordination and scheduling and emphasizes the need to integrate this access to the human on all the platforms to ensure science integrity.

AN1.5.3 Conclusion

One of the expected outcomes of a plan for coordinated access to human subjects is a process to maximize the use of the human subject. This is contingent on a well-defined ConOps for integrating and coordinating the access to human subjects. The ConOps includes understanding the roles of the personnel involved, understanding the basic process for identifying research conflicts and developing research complements and the execution of all pre-, in- and post-flight testing for the crewmembers.

Understanding how spaceflight affects human health and performance is critical for NASA and for sustained space exploration campaigns. The complexity of future crew operations on other planetary surfaces and the coordination that will be required across programs and stakeholders is far greater than current operations on the ISS. An AHRCWG and coordinating integration of human subjects data collection across Artemis programs and platforms is a key enabling capability to ensure crewmember's time and efforts in volunteering for human research during Artemis missions is maximized. This group may be chartered out of the Artemis Utilization Coordination Panel and/or coordinated with the applicable Programs.

TABLE AN1.5-1 INTEGRATED CREW RESEARCH CORRELATED REQUIREMENTS, DATA BOOKS, AND/OR TRADE STUDIES

	Requirements (HEOMD-004) *denotes products are in process at time of this publication	
AN1.5 INTEGRATED CREW RESEARCH	HEO-R-17	Crewed In-Space Duration
	HEO-R-TBD	Artemis Extended Mission Duration Requirement
	HEO-R-23*	Habitable Asset Delivery to the Lunar Surface

AN1.6 ROBOTIC UTILIZATION FOR HEO ASSETS

AN1.6.1 Importance

Lunar surface utilization offers profound benefits to NASA and partners, including unprecedented opportunities for revolutionary scientific discoveries as defined in the *Artemis Plan* and elucidated in the *Artemis III SDT Report*.

Other objectives include demonstration of capability for future Artemis missions to enable voyages to other destinations, for example resource identification, characterization, and utilization enabled by uncrewed assets is a critical component of Moon and Mars exploration. Logistics and resupply to enable long-duration activities in support of crewed surface missions; construction and assembly on the lunar surface, including landing and launch platforms and other infrastructure; mission-enabling activities such as navigation and communications; and long-term science investigations beyond the initial objectives outlined in the *Artemis III SDT Report*.

In this context, a robotic asset is defined as anything that can be operated independently of human presence on the lunar surface and in cislunar space. The use of a continuum of robotic assets in cislunar space is needed to realize the objectives above through Artemis missions. The purpose of this section is to describe the potential utilization benefits and applications for robotic assets, and the architecture needs to enable full utilization using robotically-controlled HEO assets.

Artemis includes both science rovers launched under Commercial Lunar Payload Services (CLPS), as well as HEO assets that can be operated in uncrewed modes such as LTV and PR.

In this section, the focus is on robotic utilization of HEO assets; however concurrent, integrated, and synergistic use of multiple assets could become an important enabling capability, and should be further considered as these available assets become further developed and better defined.

Uncrewed operations of surface mobility vehicles such as LTV and PR offer a significant potential to increase the safety, success, and utilization value of crewed missions. The following activities that could be completed by robotics and telerobotics, such as LTV and/or PR, in the absence of crew would contribute to that value if the necessary science instruments can be integrated.

a. *Ground truth* local lighting and thermal environments at local highly illuminated locations for future human systems and near and around shadowed regions and assess Earth view.

b. *Validate* potential traverse paths and provide initial context for scientific sites of interest for future crewed missions.

c. *Survey* the subsurface to understand the geologic layering and the presence of frozen volatile ice.

d. *Sample* collection of rocks, and possibly regolith, for further analysis by crew or return.

e. *Measure* geotechnical surface properties or sample characteristics and a wide variety of other scientific measurements.

f. *Emplace -see section e of "critical parameters that enable robotic utilization of the surface mobility vehicle such as LTV"].*

g. *Revisit* targets visited by crew for follow-up data acquisition.

h. *Prepare* landing sites for human activity by surveying and mapping the terrain and pre-positioning and emplacing surface assets and services (e.g., communication/navigation beacons, lighting, surface imagery, logistics, power, etc.).

AN1.6.2 Capability Enablers

a. *Landing site and location on the lunar surface*: Exploration and development of the lunar south polar region has been prioritized for the first crewed mission and Artemis Base Camp (HEOMD-007). However, eventually, both polar and equatorial locations could be explored with crewed or uncrewed assets. Assets could also be either mobile or stationary and could include long-duration mission capabilities (SHs, PRs).

b. *Cislunar space assets*: Missions to cislunar space, which includes both low-lunar orbit (LLO) and the Near-Rectilinear Halo Orbit (NRHO), could include Gateway, Gateway logistics missions, or other assets, such as contemporaneous orbital precursor/reconnaissance missions, navigational constellations, and communication relays.

c. *Low-Earth orbit precursors*: Robotic assets could be tested at the ISS.

d. *Ground support*: All missions will require Earth-based support through assets ranging from communication stations, support facilities, and various mission operation centers. These facilities will support dedicated science and payload teams across NASA and possibly in the external community.

The following critical parameters or variables enable robotic utilization of the surface mobility vehicle such as LTV and PR:

a. Secure communications, both to Earth, either direct or via an orbital relay asset, and to and amongst surface assets, with the capability of transferring simultaneous data including instrument data and high definition video and facilitating periods of near real-time operations.

b. Sufficient power to survive through the lunar night and operate in predominantly shadowed regions for the periods required to do science.

c. Telerobotic operation, including a demonstration of semi-autonomous navigation and operations, and a demonstration of construction and assembly operations.

d. Ability to telerobotically traverse many 10s of km, eventually and over time, with on-board hazard avoidance and navigation.

e. Interfaces for manipulation capabilities to facilitate small cargo handling, assembly, and sample handling/transport, and pointing and precision emplacement of scientific instrumentation.

f. Sufficient allocated mass, power, volume, and thermal control on surface mobility vehicles such as LTV and PR for science instruments and equipment, and sample stowage.

g. Standard interfaces on rover attachment points for interchangeable science instrumentation such as mast-mounted imaging systems (e.g., multi-spectral imagers), chassis- and arm-mounted sampling equipment (e.g., robotic arm, drill), and chassis-mounted surveying instruments (e.g., ground-penetrating radar, neutron spectrometer).

h. Data collection and storage (e.g., imagery).

Table AN1.6-1 shows a broad assessment of mission-enabling parameters deemed critical for the above activities and their impact on mission success.

TABLE AN1.6-1 ACTIVITY DEPENDENCE OF ENABLING PARAMETERS

Uses	Verify	Validate	Survey	Sample	Measure	Emplace	Revisit	Prepare
Capability								
Secure Comm to Surface Asset	●	●	●	●	●	●	●	●
Secure Comm to Earth	●	●	●	●	●	●	●	●
Survive the Night Power	●	●	●	●	●	●	●	●
Telerobotic	●	●	●	●	●	●	●	●
Robust Traverse Capability	●	●	●	●	●	●	●	●
Able to Manipulate				●	●	●		●
Arm Precision Point & Placement	●			●	●	●		●
Utilization Mass, Power, Volume	●	●	●	●	●	●	●	●
Attach Points	●	●	●	●	●	●		●
Data Collection, Storage	●	●		●	●		●	●

As outlined by the NASA *Artemis Plan* and the *NASA's Plan for Sustained Lunar Exploration and Development* , it is expected that HEOMD systems which could plausibly be operated remotely include a variety of systems, such as pressurized and unpressurized rovers, habitation systems, surface laboratory instrumentation, deployed surface experiment packages, ISRU equipment; landers, rovers and other assets landed before human missions to the lunar surface. Use cases will eventually be developed for these systems.

AN1.6.3 Conclusion

NASA's HEOMD will conduct missions to the surface of the Moon and cislunar space. Some HEOMD assets will be natively robotic; others will be crew-tended (e.g., surface habitats). Uncrewed operations of crew-tended assets would comprise most operational usage during early, short-duration crewed missions, maximizing use of these assets and enhancing return from these early Artemis surface operations. By developing robust assets capable of supporting uncrewed, remote operation, HEOMD will increase the scope of lunar surface activities while gaining essential data, capabilities, and expertise that will eventually be applicable to human missions to other destinations. This will include scientific exploration in support of and independent of human exploration; resource identification, characterization, and utilization;

technology development and infusion; construction, assembly, and logistics; and communications and public engagement. Use of remotely controlled HEOMD assets will begin prior to the first human-landed mission and continue through the sustainability phase and can support all of these stakeholder objectives.

Stakeholders who will benefit from or be involved with robotic utilization of HEO assets include the scientific community; commercial entities; international partners and other US government agencies; the NASA Mission Directorates (HEOMD – carry out safe and successful missions to the lunar surface; STMD – facilitate technology development and infusion; SMD – achieve science objectives articulated in *Artemis Plan*, *Artemis III SDT report*, and Decadal Survey science objectives); and students and the general public.

The objectives of the Artemis missions require a broad continuum of uncrewed assets and their successful robotic operations on the lunar surface, in LLO, and in cis-lunar space. Uncrewed capabilities will evolve over time as mission requirements and technologies advance, introducing new use cases that will be developed. Robotic operations on the surface of the Moon and in cislunar space are expected to enable sustainable exploration and utilization and will facilitate meeting all of the HEOMD Utilization Goals in HEOMD-006. This includes (1) scientific exploration through the collection of additional planetary mission data, caching of new samples (rocks, regolith, possibly volatiles), and results from instrumentation data; (2) collection of heliophysics, astrophysics, and Earth data; (3) collection of biological and physical science data; (4) resource identification, characterization, and utilization; and (5) a proving ground for sustainable exploration, technology development, capabilities, workforce training, and sound operational practices.

TABLE AN1.6-2 ROBOTIC UTILIZATION CORRELATED REQUIREMENTS, DATA BOOKS, AND/OR TRADE STUDIES

	Requirements (HEOMD-004) or Data Book *denotes products are in process at time of this publication	
AN1.6 ROBOTIC UTILIZATION FOR HEO ASSETS	HEO-R-8	Lunar Systems Operations and Interfaces
	HEO-R-25	Operations in Complex Terrain
	LTV-R-5	LTV Operating Environment
	LTV-R-7	LTV Autonomous Operations
	LTV-R-8	LTV Remote Operations
	LTV-R-10	LTV Transport Mass
	LTV-R-11*	LTV Science and Utilization Capability
	CNT-R-1	Lunar Relay Communications Function
	CNT-R-2	Lunar Relay Position Navigation and Timing Function
	HEOMD-412*	Enveloping Requirements for Lunar Terrain Vehicle (LTV) and Pressurized Rover Robotic Arm

AN1.7 INTEGRATED INSTRUMENTATION STRATEGY

AN1.7.1 Importance

NASA has defined a series of objectives that address high-priority science questions and fill knowledge gaps not addressed by previous exploration efforts. These objectives build on the results from decades of science investigations and technology experiments conducted on multiple space-borne missions (e.g., Apollo, Skylab, ISS, Space Shuttle, planetary rovers) and Earth-based laboratories and field sites. NASA's human exploration campaign to the lunar surface, the cislunar environment, and ultimately Mars will address these objectives in a variety of ways.

The SMD *Artemis III SDT Report*, guiding HRP documents, and STMD ISRU activities call out science and technology experiments and demonstrations during all phases of Artemis. Future missions to the Moon's surface and to cislunar space will build on the findings from Apollo and other robotic missions through exploration of new areas on the lunar surface and via: 1) scientific experiments that address fundamental and translational scientific questions; 2) experiments and applications to understand how biological and physical systems behave, respond, and are affected by the lunar environment; and 3) experiments that demonstrate how lunar resources may be used for exploration benefits, as well as new technology development and validation testing. Science and technology activities will be conducted during lunar traverses with rovers (both crewed and uncrewed), in the SH, on Gateway, HLS, Transit Habitat (TH), Orion, ISS, in transit to and from the Moon, and during both IVA and EVA. The activities and experiments may be conducted during crewed and uncrewed phases and may require crew operation or be autonomous. Tools, instruments, scientific facilities, and the necessary infrastructure (e.g., crew time, power, data recording and transmission, stowage, environmental control) are required to enable and conduct scientific experiments or technology demonstrations at their exploration locations to meet NASA's utilization objectives.

The purpose of this section is to describe the variety of potential instrumentation modes for utilization to meet the utilization goals, and the architecture elements and capabilities that are needed to support and operate the breadth of instruments. The scope of this section includes utilization with instruments mounted, deployed, or operated from the entire range of NASA's exploration platforms (ISS, Gateway, transit vehicles, and on all HEOMD lunar surface assets). It also includes crew-operated instruments and instruments that are robotically tele-operated or partially or fully autonomous. While this section includes instruments from across the science and technology disciplines, it does not cover instrument interfaces, an area that will need to be addressed in future work.

The breadth of potential instrument applications across the different disciplines and the diverse set of environments and exploration assets that are included in NASA's ISS and Artemis platforms (Space Launch System (SLS), Orion, Gateway, TH, HLS, rovers, EVA activities, SH) presents a multi-dimensional benefit and challenge to the Artemis architecture and utilization communities. This challenge points to the need for a strategic and integrated approach to describing potential instrument use cases from across the utilization communities in order to help drive out cross-platform requirements, figures of merit, and standards for operations and performance for qualitative and quantitative comparative analyses.

AN1.7.2 Capability Enablers

The Cornerstone Capabilities defined in this section will be used across all of the lunar exploration platforms (e.g., Gateway, SH, TH, HLS, LTV, and PR) and associated utilization activities (EVA and IVA). For some studies, the tools and instruments will only be used on the lunar surface, such as for collection of geological samples. In other cases, they will be used on both surface platforms (e.g., SH) and on the Gateway and TH for studies that compare the lunar surface environment impacts on biological systems to that on the Gateway in order to study combined radiation, partial gravity, and hostile/closed environments on physiological systems. Laboratory facilities that approximate facility design in terrestrial laboratories will be used in the SH. Rack/shelf-based systems, similar to the configuration and use on the ISS, will be used in the Gateway, HLS, and PR. It is anticipated that robotic activities or EVAs will be conducted on the Gateway and TH for placement and retrieval of samples from exposure facilities, to replace instruments, and to measure lunar dust on its surface. In addition, the Gateway and TH may be used as a platform for launching small satellites.

Mission and mission phase: Utilization activities, including planning, developing, flying, deploying, and operating instruments, will begin prior to the first human-landed mission and continue through sustainable Artemis phases.

a. *Pre-mission*: From Earth, development of instruments and adapting best practices and instruments from ISS utilization, training crew and operators, baseline data collection.

b. *Inflight – transit*: Instruments for data collection and monitoring of crew health.

c. *Gateway and TH – crewed*: Instruments for human research data collection, monitoring of crew health and performance, and biology and physical science experiments in deep space.

d. *Gateway and TH –uncrewed*: Externally mounted instruments to observe and collect data from the designated environment (e.g., deep space, the heliosphere, the Moon, the Earth), internal monitoring instruments, and biological or physical science experiments in deep space.

e. *Lunar surface – crewed*: Instruments for data collection and monitoring of crew health and performance, biology and physical science experiments in deep space, instruments used for the exploration of the lunar surface on traverses, deployment of short-duration (mission length) and long-term scientific instruments.

f. *Lunar surface – uncrewed*: Long-duration instrument data collection.

To illustrate instrument utilization across the variety of missions and mission phases, NASA has identified and developed several use cases to demonstrate the kinds of HEO assets needed to enable utilization.

> *Use Case 1a: Instruments (facility) for use inside a habitable volume*. This use case captures facility mounted instruments that may be used inside Orion, Gateway, HLS, a PR, and the SH. Examples include a glovebox, medical diagnostic instruments, *in situ* analysis hardware (blood/urine analysis, Deoxyribonucleic Acid (DNA) sequencing, microscope), crew-worn sensors (actigraphy, physio), radiation monitors, accelerometers (load sensors), environmental sensors (internal/external), vehicle audio/video recording, and computer-

dependent data collection software/hardware. Sample analytical instruments include spectroscopy instruments, chemical analytical instruments, etc.

Use Case 1b: Medical instrumentation for use inside the habitable volume. Medical instrumentation involves a collection of instruments that can be utilized by both the medical and research communities to evaluate the crews' physiological, behavioral, and/or environmental conditions from the longer-duration and micro-/partial-gravity exposures during the mission. The medical diagnostic instrumentation may both provide invasive or non-invasive monitoring capabilities, environmental monitoring of the internal volumes of the various vehicles and platforms, and the ability for the NASA research communities to evaluate the efficacy of countermeasures as NASA prepares to travel beyond the Moon and to Mars.

Use Case 2: Surface instruments (deployed, rover-mounted, HLS-mounted). This use case captures instruments intended to be used on the lunar surface, whether deployed via crew during EVA, carried during a traverse experiment, or hard mounted to either HLS or a pressurized or unpressurized rover. SMD instrument examples include geophysical and environmental monitoring, traverse instruments such as Light Detection and Ranging (LiDAR) and magnetometers, as well as facilities to investigate the effects of long-term exposure of materials to the lunar surface environment. STMD examples include a deployed ISRU package. HEOMD/HRP examples include radiation monitoring, accelerometers, environmental sensors (internal/external), and vehicle audio/video recording. Such so-called "suitcase science" experiments could either be fully self-contained (e.g., Apollo Lunar Surface Experiment Packs or ALSEP) or rely on other surface assets for power and/or communication.

Use Case 3: Portable/handheld instruments. This use case captures portable instruments that may be used both internal and external to the habitable volume. Examples include cameras, handheld field instruments like X-ray Diffraction or X-ray Fluorescence spectrometers, neutron spectrometers, visible/near-infrared/thermal-infrared spectrometers, and instruments for assessing volatile release during sampling activities.

Use Case 4: Orbital instruments. Like ISS, the Artemis program provides an infrastructure capable of providing external payloads valuable for short- to long-term access to space. This use case captures instruments and payloads mounted externally to human exploration assets, which currently only includes Gateway but could expand to include other assets. This capability also includes remote sensing assets that would characterize the lunar surface/subsurface to complement sample collection and *in situ* analyses that take place on the Moon.

	Orbital Assets		Surface Assets		Transit Vehicles
Experiments in pressurized volume	Gateway	Surface Habitat	PR		e.g. HLS, Orion
Instrument deployed on surface			LTV, PR	EVA Systems	HLS
Portable or standalone instrument	Gateway	Surface Habitat	LTV, PR	EVA Systems	e.g. HLS, Orion
Orbital instruments	Gateway				Cubesats

FIGURE AN1.7-1 INSTRUMENT USE CASES SUPPORTED BY HEO PLATFORMS

Communications and data (open and secure): Many of the instruments described in the Use Cases will require some form of data link, either between the instrument and one or more surface assets, to a lunar communications infrastructure or Direct to Earth (DTE). The *Artemis III SDT Report,* for example, recommended that NASA provide a mission capability of real-time transmission of data from *in situ* science instrumentation that provides documentation for site characteristics and enables a science support team (e.g., backroom, operations center) to support EVA operations with (near) real-time feedback to the crew when necessary on science decision-making, as well as provide processed data or analysis when necessary (i.e., helping convert raw data into tactical decision-making). These data would include crew voice, imagery from crew cameras, video from crew mounted cameras on their xEVA Systems suits and/or pointable cameras on rovers/lander systems, data downlink (and command uplink) from (to) deployed and *in situ* experiments, navigation (e.g., surface mobility vehicles such as LTV and PR), and dual-use instruments across research and operational collections (e.g., environmental monitors). This requires prior establishment of high bandwidth communication that is capable of extensive real-time data transmission to accommodate use of valuable measurements from modern sensors.

Mobility – Crewed and Uncrewed: The south polar region of the Moon features undulating terrain, slopes that steepen or flatten at various scales, and dispersed volatile resources. Robust mobility systems will be vital to the long-term exploration and development of the Moon and are important factors for enhancing/enabling utilization objectives. For example, mobility would serve to increase the science capability of early Artemis landings by providing access to a diverse sample of geologic units and facilitating deployment of instruments/experiments over a broader area than can be accessed on foot during a single EVA. Mobility platforms allow for a greater number of instruments and associated field equipment to be carried on a traverse, giving the crew a wider assortment of tools to work with and the flexibility to apply the right tool for the job at hand. Mobility assets would also provide the capability for mounted instruments and potentially, the capability to position, point and deploy instruments.

IVA Support: A broad range of science experiments will be conducted on the lunar surface, which may require laboratory facilities on the Moon in a habitable environment, such as gloveboxes, discipline-specific facilities (e.g., Human Research Lab), conditioned stowage, and general, multi-purpose use areas. The types of tasks that may be conducted include, but are not limited to, incubation of biological specimens, specimen processing; *in situ* analyses; human physiology and lunar adaptation; physical sciences studies; lunar geological specimen handling and analyses; and microbial ecosystems and survivability sample collection. These utilization activities will require both common-use and unique instruments, facilities, resources (consumables and non-consumables), and science experiment hardware. IVA support capabilities including standardized systems and interfaces, rack systems, stowage for instruments and consumables, power, multi-use facilities like gloveboxes, and access to gases and heat rejection represent the baseline utilization capabilities necessary for conducting experiments and other utilization activities on the Moon.

xEVA Capability: A key element of planetary exploration by humans is the capability for astronauts to walk on the surface, the flexibility and range of motion to make observations, collect data and samples, and deploy instrument packages. This capability is made possible by exploration extravehicular systems that includes the spacesuits, tools, the vehicle interfaces, other accessories, and mobility assets such as rovers. The xEVA systems are being designed to work on the lunar surface and maximize human exploration. xEVA systems may include attachments on/in the spacesuits and helmets: navigation, displays, and communications with surface assets and the Earth; tools and carriers for instruments; support with rovers to increase surface accessibility and carry or attach instruments; and crew training to use and deploy instruments in support of mission science and technology objectives. Communications, interfaces, navigation, and crew time for training and operations are all critical capabilities for an integrated instrument strategy.

Power: The instruments described in the use cases universally require power. While some instruments may not have any power needs (e.g., retroreflectors, passive collection devices), most instruments could be either self-contained (i.e., they carry their own power supply) or require power from other assets (e.g., HLS, LTV, SH, Gateway, TH, PR). Initial HLS missions are expected to be limited in their capability to support powered payloads. Furthermore, long-lived experiments, which would address many high-priority utilization objectives, require operations over time periods longer than the surface missions themselves. Power sources that enable instruments to survive and operate through the lunar night are critical to accomplishing utilization objectives, and lunar night operations are essential for a sustained presence on the Moon. In particular, science operations in lunar polar regions, particularly in permanently shadowed regions and through the passage of the terminator, rely on the power capabilities encompassed by operating through the lunar night.

Conditioned Stowage and Transport: Utilization will require conditioned stowage spanning +4°C refrigeration to freezer use (-20°C to -80°C or lower) and cryogenic temperatures (see Table AN 1.2-1). It is important to note that the temperature used to maintain the specimens in the laboratory will need to be maintained from collection through transportation back to Earth and during transport from splashdown to curatorial facilities or analytical laboratories.

The ability to transport a sample from the surface of the Moon to curation or terrestrial analytical facilities while continuously maintaining temperatures low enough that water ice and other volatiles remain in the solid state with a low vapor pressure adds considerable value to sample return, such as the studies of volatile elements or biological specimens. Cold and cryogenic transport and curation will preserve aspects of the form, texture and chemistry of the samples that can be erased and/or compromised by biological reactions at higher temperatures or reactions between liquid or gaseous H_2O and other volatile compounds.

In addition to temperature, other utilization may require control of other parameters such as humidity, pressure, vibration limits, etc.

Interoperability across Artemis platforms: Interoperability will be a critical consideration when developing instrument utilization strategies. Factors to assess include, but are not limited to, interfaces, common data formats, common application programming interfaces, design considerations like rear-breathe vs. front-breathe, power, communications, and capabilities for in situ repair and/or substitution of scientific payloads or parts previously deployed on the surface, if payload architecture allows. As a downmass consideration, there is a desire for multi-purpose instruments that address objectives from multiple stakeholders, as well as instruments that can be used on multiple platforms (e.g., Gateway and SH).

Pre-deploy: Mass allocations expected to be available on the HLS system for delivery of tools and payloads to the lunar surface, especially for the initial surface missions, may be insufficient to achieve the full spectrum of utilization objectives outlined by the stakeholder community. A portion of the downmass allocation will always be reserved for sample collection tools and containers, the latter of which also comprise part of the upmass allocation. The ability to pre-deploy utilization assets using a robotic lander (e.g., CLPS, Deep Space Logistics (DSL), Artemis Demo Mission) would dramatically increase the capability of early Artemis missions to that site, but it's dependent upon being able to confirm landing sites far in advance. The pre-deploy mission could carry an inert cache of tools/instruments to be accessed by crew upon arrival, one or more instrumented landers or rovers for environmental monitoring, a power source for the instruments described in the Use Cases presented here, or other enabling capabilities.

Automated Environmental Monitors: Long-duration environmental monitoring captures exosphere measurements relevant to both the character and origin of lunar polar volatiles and secondary emissions due to solar wind impact, as well as assessment and mitigation of exploration risks associated with space weather. Observations from the surface should be coordinated with measurements from orbit to reveal connections between processes on different scales, and the nature of the radiation variability and shielding. In addition to external environmental monitors, data collected from automated monitors of habitable volumes will enable utilization analyses. Wherever possible, the Artemis program should leverage operational capabilities such as radiation monitors, CO_2, O_2, temperature, humidity, and other sensors that address the utilization goals of other stakeholders.

AN1.7.3 Conclusion

The Artemis architecture, including uncrewed and crew-tended platforms, will provide an unprecedented variety of infrastructure for science and technology instrument integration, deployment, and operations. The breadth of scientific instrument types, modes, and locations that will be deployed to achieve Artemis objectives and the implications for the entire Artemis architecture, from ground operations to the lunar surface and cislunar operations, requires a holistic assessment and integrated approach for instrument accommodations, starting with the earliest phases of planning. By developing robust plans for utilization with instruments deployed and operated in a variety of environments and operational modes, HEO will enable a broad portfolio of exploration of deep space, planetary surfaces and collect valuable data, capabilities, and expertise that will eventually be applied to human missions to other destinations, such as Mars.

Many stakeholders are invested in an integrated instrumentation strategy for Artemis Utilization, including cross-NASA stakeholders.

a. *HEOMD*: HEOMD's HRP and the biomedical community require an integrated strategy in order to keep the crew healthy, understand crew health and performance parameters in a variety of environments, assess crew health mitigation strategies, and prepare for missions to Mars. In addition, an integrated strategy will allow HEOMD to carry out safe and successful missions to the lunar surface and achieve priority mission objectives.

b. *STMD*: There will be a benefit from an integrated instrument strategy for technology development, *ISRU*, and infusion for living in space and exploring new destinations.

c. *SMD*: The scientific community will benefit by enabling mission success through achievement of the science objectives articulated in the *Artemis Plan, Artemis III SDT Report, National Academy of Sciences Decadal Surveys, Space Weather Science and Observations Gap Analysis for NASA*, and other key community documents.

d. *OCE: Space Weather Architectures for NASA Missions, An Assessment of Space Weather Architectures to Support Deep Space Exploration* , and the *Safe Human Expeditions Beyond Low Earth Orbit Workshop Report*.

e. Outside of NASA, partners from other government agencies, the commercial sector, and international partners will benefit by the requirements spelled out through an integrated instrument strategy.

f. American taxpayers will benefit through the science and technology results and the efficiencies gained by developing an integrated strategy for planning, developing, and operating scientific and technical instruments in all phases of Artemis.

The expected outcome of an integrated instrumentation strategy is critical to achieve all utilization goals; exploration and utilization across disciplines will take full advantage of the Artemis architecture. Outcomes include data for open science use; collection of data to understand human systems, and crew health and performance to enable human missions to Mars; new technology demonstrations to enable sustainable exploration; resource identification, characterization, and utilization.

TABLE AN1.7-1 INTEGRATED INSTRUMENTATION STRATEGYCORRELATED REQUIREMENTS, DATA BOOKS, AND/OR TRADE STUDIES

	Requirements (HEOMD-004 and Data Book) *denotes products are in process at time of this publication	
AN1.7 INTEGRATED INSTRUMENTATION STRATEGY	HEO-R-2	Audio and Imagery
	HEO-R-8	Lunar Systems Operations and Interfaces
	HEO-R-12	Utilization Payload Delivery to the Lunar Surface
	HEO-R-14*	Conditioned Sample Return from the Lunar Surface
	HEO-R-16	Communications to Earth
	HEO-R-23*	Habitable Asset Delivery to the Lunar Surface
	Gateway-R-5	Gateway Uncrewed Operations
	Gateway-R-8	Gateway Science Experiment and Technology Demonstration Accommodation
	CNT-R-1	Lunar Relay Communications Function
	HEOMD-411*	Enveloping Requirements for Lunar Terrain Vehicle (LTV) and Pressurized Rover Science Instruments

AN1.8 COMPLEX OPERATIONS IN COLD/SHADOWED REGIONS AND VOLATILE-BEARING TERRAIN

AN1.8.1 Importance

One of the most significant findings of planetary science of the last two decades has been the distribution of water on airless bodies in the inner Solar System. PSRs near the poles of the Moon and other planetary bodies (e.g., Mercury, Ceres) may harbor water and other volatiles in quantities that can enable sustained exploration. The science and technology aspects of finding, characterizing, extracting, refining, and eventually using *in situ* resources will drive the future of human exploration. A comprehensive ability to explore PSRs enables the full spectrum of science, exploration, commerce, and technology developments. Given the overall integrated nature of PSR operations and the necessity to operate in the extreme environmental regions in which these volatile resources exist, it is a significant enabler of future missions to planetary surfaces.

The purpose of this section is to identify the cross-cutting use cases for conducting operations in PSR environments, then identify the various applications of those use cases for the major stakeholders, and in achieving the identified utilization goals. The scope is to: 1) attempt to capture all user needs for PSR operations, 2) identify the integration of the various user needs for PSR operations, and 3) define initial plans for PSR operations in directly addressing utilization goals and objectives.

AN1.8.2 Capability Enablers

Four use cases for PSR operations were identified that address the stated purpose and scope. These were largely derived from the review and summary of existing documents and resources on this topic. These four use cases represent cross-cutting themes that are intended to capture all user needs while also addressing the utilization goals and objectives. The four use cases are summarized in Figure AN1.8-1 and further described below:

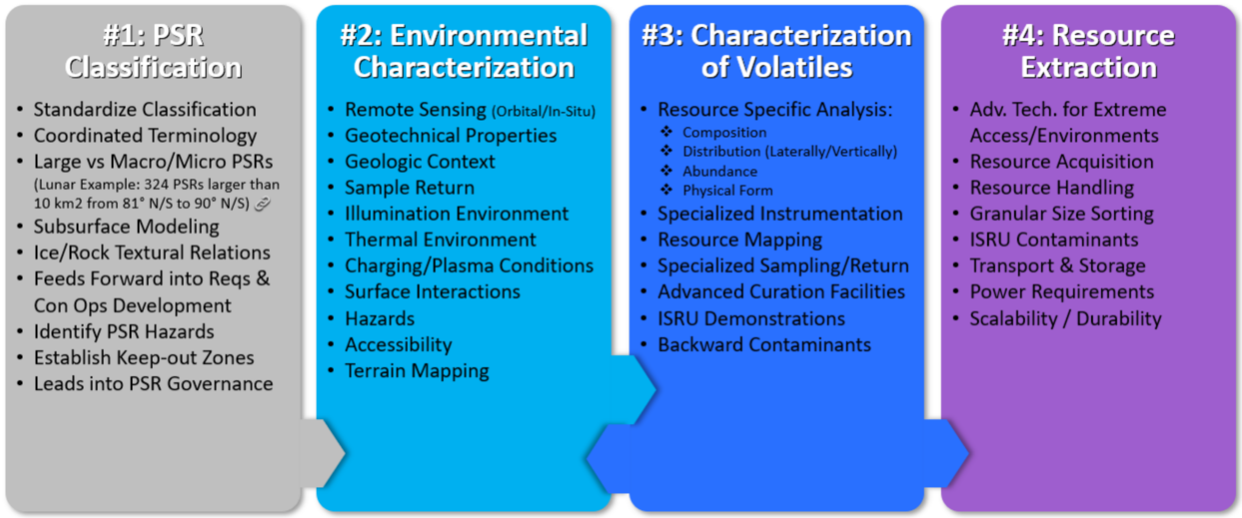

FIGURE AN1.8-1 USE CASE SUMMARY FOR PSR OPERATIONS

Use Case 1: PSR Classification

One of the fundamental initial steps in PSR operations is the need for an integrated strategy for a standard classification of the types of lunar PSRs. A coordinated classification strategy that standardizes terminology across the various stakeholders and documents would greatly facilitate communication. These efforts will also help define hardware requirements and ConOps. In addition, topics such as identifying associated PSR hazards, keep-out zones, planetary protection requirements, and governance would greatly benefit from an integrated classification scheme.

Use Case 2: Environmental Characterization

The environmental characterization use case is intended to capture the analysis, products and capability required to characterize the overall PSR environment (e.g., temperature ranges, sky view) both remotely and from the surface. Figure AN1.8-1 outlines some of these aspects, including characterizing the unique illumination, thermal and charging/plasma environment of PSRs. This type of environmental characterization is, and will be, an integrated iterative approach and will include orbital and lander/rover robotic assets as well as human exploration missions.

Use Case 3: Characterization of Volatiles

The characterization of volatiles in this use case is intended to capture the resource-specific analysis required for fundamental science as well as ISRU purposes. Figure AN1.8-1 outlines some of these aspects, including characterizing the composition, distribution, abundance, and physical form of volatiles within PSRs, along with the special requirements for sample collection and preservation that enable resource-focused exploration efforts.

Use Case 4: Resource Extraction

The resource extraction use case is intended to capture the technologies and capabilities required for the *in situ* extraction of volatiles for utilization purposes in a PSR environment. This use case assumes that the resources identified in use case 3 are now targeted for extraction during dedicated PSR operations that would require specialized handling, transport, and storage technologies for return to Earth or ISRU (e.g., *Lunar Water ISRU Measurement Study (LWIMS)*). In addition, advanced technologies for extended durations in increasingly more extreme PSR environments, along with the associated corresponding increased power requirements, are also a major component of this use case.

Figure AN1.8-2 depicts the locations required for PSR operations, as well as the rationale for HEO involvement (“Why”) for PSR operations, and the impacts to HEOMD hardware and elements.

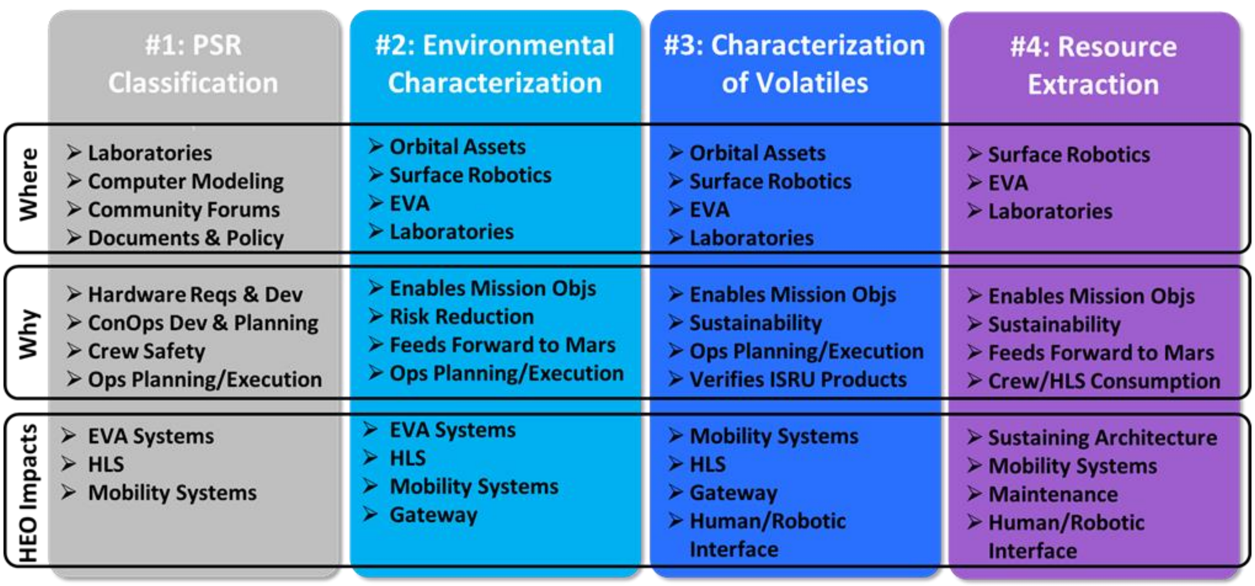

FIGURE AN1.8-2 LOCATIONS NEEDED (WHERE) AND RATIONALE FOR HEO

Figure AN1.8-3 graphically depicts the time dependencies of current and planned lunar investigations, as well as a notional deployment schedule for architectural Artemis elements. Information and technology needs are depicted on the notional timeline for when they would be required.

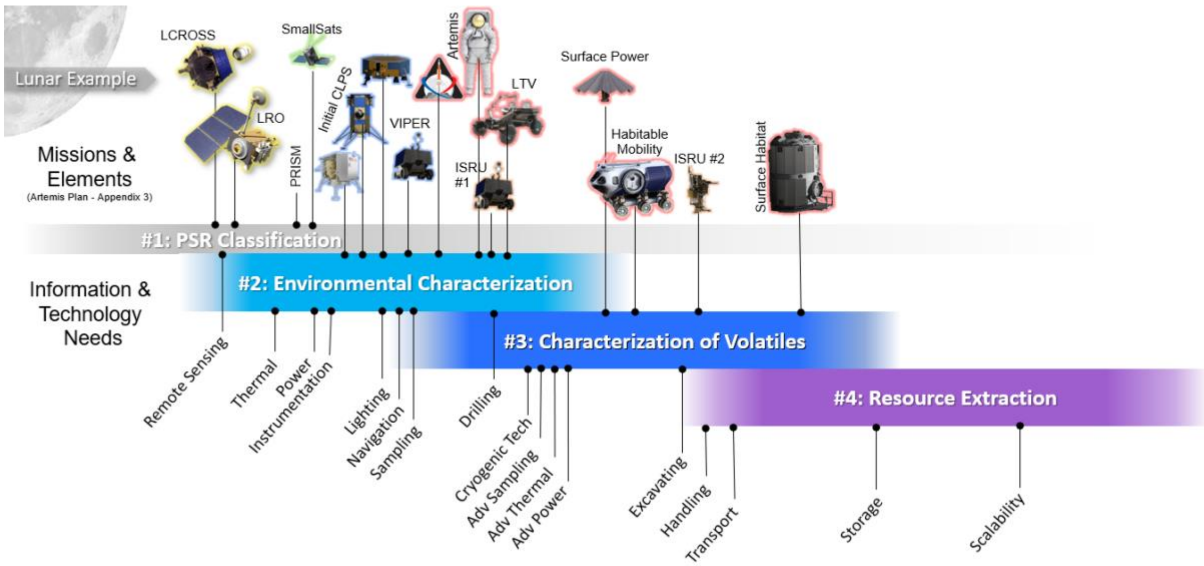

FIGURE AN1.8-3 TIME DEPENDENCIES OF OTHER INVESTIGATIONS, DEPLOYMENT SCHEDULE OF REQUIRED ASSESTS/ARCHITECTURE BUILDUP, ECT. FOR PSR OPERATIONS

AN1.8.3 Conclusion

Major stakeholders for PSR operations and capabilities include NASA missions' directorates (SMD: To achieve science objectives articulated in *Artemis Plan*, *Artemis III SDT Report*, and Decadal Survey science objectives. This category includes input from the greater scientific community; HEOMD: To facilitate mission objectives and ensure safe operation for crewmembers; STMD: To facilitate technology development and infusion); and Commercial, Interagency and International Partnerships: To help make exploration more affordable and sustainable, grow new markets, and increase capabilities.

Figure AN1.8-5 illustrates the alignment of PSR operations use cases to the utilization goals and objectives. Broadly, there is strong alignment within each goal to the four use cases.

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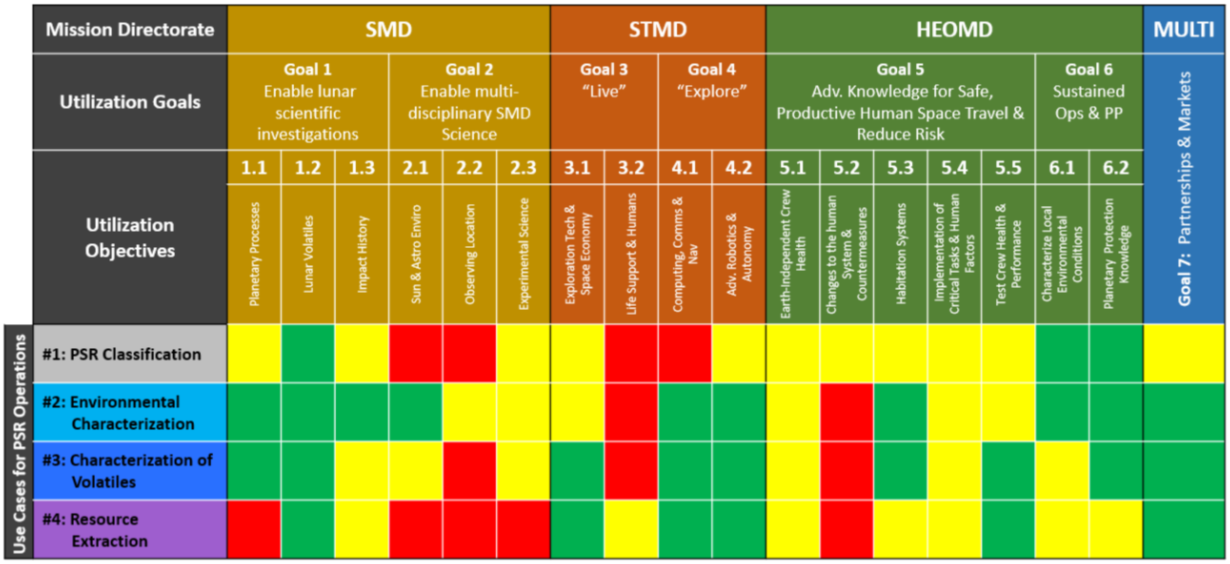

Green = Strong Use Case Alignment, Yellow = Moderate Use Case Alignment, Red = Little/No Use Case Alignment

FIGURE AN1.8-4 USE CASE ALIGNMENT TO UTILIZATION GOALS AND OBJECTIVES FOR OPERATIONS IN COLD/SHADOWED REGIONS

Human exploration of planetary surfaces will increasingly depend on access to unique surface environments such as dark and cold regions of the lunar surface; exploration science and sustainability will be enabled by characterizing and extracting the potential resources in these locations. Operations in the extreme and scientifically rich environments of PSRs will require integration across the exploration campaign and exploration assets.

TABLE AN1.8-1 COMPLEX OPERATIONS IN COLD/SHADOWED REGIONS CORRELATED REQUIREMENTS, DATA BOOKS, AND/OR TRADE STUDIES

	Requirements (HEOMD-004)	
AN1.8 COLD & SHADOWED OPS	HEO-R-25*	Operations in Complex Terrain
	LTV-R-5	LTV Operating Environment

S1.0 ANNEX 1 SUMMARY

The Cornerstone Capability descriptions in this annex reference their dependencies on various hardware elements or programs included in the Artemis architecture (see Table AN1-S1-1). This summary highlights the multi-platform, multi-program reach for each of the Cornerstone Capabilities, and the need for an integrated assessment in order to support the utilization goals and objectives specified by HEOMD, SMD and STMD.

TABLE AN1-S1-1 CORNERSTONE CAPABILITY DEPENDENCIES

Cornerstone Capability Dependencies											
Category	Transit (crew/logistics/samples)			Lunar Surface				Extended Missions			
Major utilization function	Transit (crew/logistics/samples)		Cargo Logistics	Surface Utilization	Early Mobility	Surface Mobility	Sustained Timeline	Sustained Timeline	Transit	Moon to Mars Forward	
Hardware Element	Orion	HLS	Cargo	xEVA	LTV	Press. Rover	Surface Habitat	Gateway	Transit Habitat	ISS	Comm. LEO
Element Feed Forward for Mars	●(red)		●(red)	●(red)		●(red)		●(red)	●(red)	●(red)	●(red)
1.1 Exploration Traverses	○	◉	◉ ◉(red)	● ●(red)	●	● ●(red)	◉	○			
1.2 End-to-End Sample Return Strategy	● ●(red)	●	◉ ◉(red)	● ●(red)	●	● ●(red)	●	◉ ◉(red)	●(red)	○ ●(red)	◉ ●(red)
1.3 Planetary Protection	◉(red)	◉(red)	○(red)	◉ ◉(red)	○(red)	◉(red)	◉ ●(red)	●(red)	●(red)	◉(red)	●(red)
1.4 Extended Missions	◉ ◉(red)	● ●(red)	◉ ◉(red)	● ●(red)	●	● ●(red)	● ●(red)	●(red)	●(red)	● ●(red)	◉ ●(red)
1.5 Integrated Crew Research	● ●(red)	● ●(red)		● ●(red)	○	◉ ◉(red)	● ●(red)	●(red)	●(red)	● ●(red)	○ ●(red)
1.6 Robotic Utilization	○	○	○	○ ○(red)	●	● ●(red)	●	◉		◉	
1.7 Instrument Strategy	●	●	◉ ◉(red)	● ●(red)	●	● ●(red)	●	● ●(red)	●(red)	● ◉(red)	◉ ●(red)
1.8 PSR Operations	○	◉	◉	● ○(red)	●	●	◉	○			

Key	Moon	Mars Relevant
Essential: critical for capability	●	●(red)
Enhancing: not a critical dependency but highly enabling	◉	◉(red)
Supporting: adds capability for human exploration	○	○(red)

In the above table, the enabling capability dependencies on different human exploration elements are mapped, and identified as essential (critical for capability), enhancing (not a critical dependency but highly enabling), or supporting (adds capability) for human exploration of the lunar surface (in black) and Mars (in red).

The descriptions and use cases in this annex also identified "enablers" — operational functions, sub-systems and architecture attributes that are required for successful utilization (see the "Capability Enablers" section for each description). Table AN1-S1-2 summarizes these "Enablers" as they apply to each of the Cornerstone Capabilities.

TABLE AN1-S1-2 ENABLING ATTRIBUTES REQUIRED FOR UTILIZATION

		Cornerstone Capabilities							
Category	Enablers	1.1 Exploration Traverses	1.2 Sample Return	1.3 Planetary Protection	1.4 Extended Missions	1.5 Crew Research	1.6 Robotic Utilization	1.7 Instrument Strategy	1.8 PSR Operations
Comm and Nav	Communications - Bandwidth	●			●	●	●	●	●
	Communications - FCT Access	●	●		●	●	●	●	●
	Comm Between Surface Assets	●	●		●		●	●	●
	Navigation	●	●				●	●	●
Mobililty	Mobility - Crew xEVA	●	●			●		●	●
	Mobility - LTV	●	●			●	●	●	●
	Mobility - Pressurized Rover(s)	●	●		●	●	●	●	●
	Mobility - Robotic	●					●	●	●
Systems Elements	Power	●	●		●	●	●	●	●
	Thermal Control		●		●	●	●	●	●
	Stowage	●	●	●	●	●	●	●	●
	Standard Interfaces	●			●	●	●	●	
	Surface Lighting	●	●				●	●	●
Payload and Sample Needs	xEVA Tools	●	●	●				●	●
	Cargo Manipulation Ability						●		●
	Precision Pointing						●	●	●
	Payloads	●		●	●	●	●	●	●
	Delivery Mass/Vol Pre-deploy	●					●	●	●
	Delivery Mass/Vol w. Crew	●	●	●	●	●	●	●	●
	Return Mass/Volume		●	●	●	●		●	●
	Contamination Control		●	●	●	●		●	●
	Planetary Protection		●	●	●	●	●		●
	Conditioned Stowage	●	●	●	●	●		●	●
	Sample Transport	●	●	●	●	●		●	●
Crew Time	Crew Time - Earth		●	●	●	●		●	
	Crew Time - Transit		●	●	●	●		●	
	Crew time - Surface		●	●	●	●		●	●
	Crew time - Habitat	●	●	●	●	●		●	
Data	Auto Data Capture/Transmit	●	●	●	●		●	●	●
	Data Visualization	●					●	●	●
Mission attributes	Long-Duration Mission	●		●	●	●	●	●	●
	PSR Access and Operations	●	●				●	●	●
	Landing Site Dependency	●	●				●	●	●

While this table is a snapshot of the architecture and system needs for each utilization capability, it is likely to change as the architecture evolves, and utilization requirements become better defined.

ANNEX-2
PHASING OF CAPABILITIES AND FACILITY REQUIREMENTS

<**TBD-006**>

ANNEX-3
INTEGRATED LEO MISSION-SPECIFIC UTILIZATION REQUIREMENTS

<**TBD-007**>

ANNEX-4
INTEGRATED ARTEMIS MISSION UTILIZATION OBJECTIVES

AN4.1 ARTEMIS FIRST LANDED MISSION

Artemis Mission-Specific Utilization Requirements: First Crewed Lunar Landing

The following strategic requirements are identified for utilization during the first crewed landing of Artemis. These high-level requirements document SMD, STMD, and HEOMD's objectives to be completed on the mission and represent an agreement on joint utilization planning. These requirements were developed through the Utilization Coordination and Integration Group (UCIG). Because these requirements are baselined in the strategic timeframe and use current knowledge of HLS and Orion capabilities, these capabilities may change as hardware is developed and missions are refined. These requirements identify the agreements between mission directorates that flow to implementation plans but will not require formal engineering verification. These requirements are not intended to drive program design requirements, as those requirements are to be documented in HEOMD-004.

Feasibility and implementation of these requirements will be coordinated by the Artemis Utilization Coordination Panel (AUCP) and governed by the Advanced Exploration Systems (AES) Division and Exploration Systems Development (ESD) control boards. As both capabilities and specific science objectives are refined, if there is a significant deviation from these requirements, the AUCP or division control boards will elevate the issue to the UCIG and HEO Systems Engineering and Integration to engage the appropriate tri-mission directorate consultation and decision forums.

Considerations and Assumptions from Pre-existing Program Requirements

HLS-RQMT-001 in the *HLS Program System Requirements Document*, dated 3 November 2020, established a minimum of 100 kg downmass for utilization for the first crewed lunar landing mission. However, the allocation between different types of tools, instruments, and containers shown as an example in HLS-RQMT-001, Table 11, is to be rebalanced when the specific science is identified. Additional downmass, if it becomes available, would significantly enable science investigations. While referenced in Table 11, no "cameras or other sensors for use in the habitable environment" are required for utilization on this mission.

ESD-R-8 in HEOMD-004, *Human Exploration Requirements*, established a 100 kg minimum pressurized cargo return mass for an Orion crew of four, which is also used in this document for planning purposes. Additional return mass, if it becomes available, would significantly enable science investigations and is strongly desired by the science community.

Additional small utilization-related items may be returned to Earth if the Orion manifest can support (e.g., if more trash can be offloaded or if exactly 100 kg is not used by the objectives below). Several items could fall into this category (e.g., dosimeters, seed packets, or pharmaceuticals).

Crew Time

It is understood that crew time is necessary for most of the utilization requirements, including lunar surface science and human research. Crew time in all mission segments, and particularly

EVA time, is likely to be a highly constrained resource. Final crew time and schedule will be managed as part of mission planning, subject to overall mission timelines and planning constraints as they are developed. Other flight resources may also be identified as limiting as mission planning continues.

Utilization Requirements

4.1.1 The mission shall return lunar samples of diverse types.

a. Specific samples to be collected and returned will be prioritized by a science team selected by SMD, working within mission capabilities, and will be dependent on the final choice of landing site and mission feasibility.

b. Geologic samples (to address Objectives 1.1, 1.2, 1.3, and 2.1) will be collected using multipurpose tools. The necessary set of geological sampling tools developed within the xEVA Project will include sealed samples and may include small and large clast samples, sealed core and surface samples, and regolith samples. Downmass for geological tools and sample containers in this requirement (4.1.1) and instruments in requirement 4.1.2 will not exceed 94 kg, depending on HLS capabilities.

c. The mass of geologic samples, including containers, from the lunar surface and for return to Earth is expected to be between approximately 29 kg and 94 kg, depending on HLS and Orion capabilities.

d. Capability to regulate sample temperatures between collection and return to Earth was desired but is not expected to be available for this mission.

4.1.2 The mission shall include deployment of instrumentation packages by the crew on the lunar surface.

a. Specific instruments will be solicited by SMD and will be dependent on the final choice of landing site and mission feasibility.

b. Instruments may measure such properties as volatiles, environmental parameters, geophysical properties, and geochemistry/mineralogy (to address Objectives 1.1, 1.2, 1.3, 2.1, and 2.3).

c. Downmass to the lunar surface for geological tools, sample containers in 4.1.1 and instruments in 4.1.2 will not exceed 94 kg, based on the HLS capabilities. Total landed mass of instruments requested will be traded with mass for sampling tools and containers once science plans are refined.

d. It is expected that none of the deployed instruments will be returned from the lunar surface.

e. Documentation from any multipurpose cameras used for safety and situational awareness may be requested to support science activities, but these cameras are not part of the mass for SMD-selected instruments. If science-specific camera equipment is identified as needed beyond multi-use cameras (e.g., cameras or lenses for EVA science-related macro or telephoto photography), this would be considered utilization and part of the 94 kg downmass.

4.1.3 The mission shall perform human research.

a. The research will be identified by HRP and will be dependent on mission feasibility.

b. Studies include effects of microgravity/partial gravity transitions, multi-day exposure to the partial gravity of the lunar surface, effects of deep space ionizing radiation on the human system, and human/systems risk characterization to inform future exploration-class missions to address Objectives 5.1, 5.2, 5.3, and 5.4.

c. Upmass of consumables/hardware/samples launched on Orion, landed on the Moon in HLS, returned to orbit in HLS, and returned to Earth on Orion is expected to be approximately 6 kg or less of ambient samples based on Orion and HLS capabilities.

4.1.4 The HLS Program shall request select data be provided by the vendor from on-board instrumentation to be used for performance and model validation by NASA.

a. The specific parameters will be identified by STMD and will be dependent on the vehicle design, sensor capabilities, and specifics of the contract with the HLS provider.

b. Studies include plume-surface interaction, precision landing technology development, and cryogenic fluid management performance to address Objective 4.1.

c. No flight resources or additional instrumentation specific to this research are required.

Additional Requirements if Gateway is Included

In addition to those listed above, if the first crewed lunar landing docks with Gateway, the following strategic requirements are identified. Because they have been baselined in the strategic timeframe and use current knowledge of Gateway, Gateway logistics upmass, and Orion return capabilities, these capabilities could change as hardware is developed and missions are refined. Gateway utilization is also subject to the utilization management process in international partner agreements, which will be managed by the appropriate forums under the Artemis Utilization Control Panel and Gateway Program.

4.1.5 The mission shall perform human research on the Gateway.

a. The research will be identified by HRP, working with Gateway international partners, and will be dependent on mission feasibility and logistics upmass capability.

b. Studies include physiological, psychological, behavioral effects and countermeasures and related research to address Objectives 5.1, 5.2, 5.3, and 5.4.

c. No additional return mass of samples/hardware on Orion is expected to be needed beyond that identified in the crewed lunar landing mission in Section 4.1.3c.

d. No additional upmass of consumables/hardware launched in Orion is expected to be needed beyond that identified in the crewed lunar landing mission in Section 4.1.3c.

e. Upmass/volume of consumables/hardware is expected to be approximately 30 kg or less if Gateway logistics capabilities are available.

4.1.6 The mission shall perform space biology research on the Gateway.

a. The research will be identified by SMD, working with Gateway international partners, and will be dependent on mission feasibility and Gateway logistics upmass capability.

b. Studies include understanding microbial ecosystems, from individual species to multi-species communities, in the deep space environment (Objective 2.3).

c. Upmass/volume of consumables/hardware depends on availability of Gateway logistics capabilities.

d. Mass of samples for return on Orion is expected to be approximately 1 kg or less and will be traded with the SMD total return mass as planning is refined.

4.1.7 The mission shall study the space environment at the Gateway.

a. The specific scientific instruments will be identified by Gateway users, including SMD and the Gateway international partners, and will be dependent on mission feasibility.

b. Research includes studying the plasma environment outside Earth's magnetosphere, characterizing solar electric particles and galactic cosmic radiation, and studying the ambient plasma and radiation environment (Objectives 2.1, 2.2, 2.3, and 6.1).

c. Instruments are expected to be launched with the Power and Propulsion Element (PPE) and Habitation and Logistics Outposts (HALO) Co-Manifested Vehicle (CMV) mission.

d. Little-to-no return mass specific to this research is expected to be required, and any mass returned to Earth would be expected to occur only if capacity is available.

TABLE AN4.1-1 SUMMARY OF PLANNING MASSES

The HLS and Orion capabilities define the mass planning allocations for the activities in this document. The total to (downmass) and from (upmass) the lunar surface is currently limited to 100 kg total for this mission. This mass was allocated to the activities as follows. STMD did not request transportation on this mission.

Downmass to Lunar Surface on HLS			
	Hardware	**Mass (kg)**	**Notes**
SMD	Total	94	Mass trade priority based on SMD priorities and input from science team selected by SMD. Includes trades to be made between tools, sample return equipment, deployed instruments, and experiments.
HEOMD	Human research	6	
TOTAL		100	
Upmass from Lunar Surface on HLS and Returned to Earth on Orion			
SMD	Lunar samples (including containers)	29 (min) up to 94	SMD priorities and sample types collected will determine the mass of containers vs. samples, depending on HLS and Orion capabilities. Includes any mass for other samples returned for SMD, such as for Biological and Physical Sciences (BPS).
HEOMD	Human research	6	
TOTAL		35 (min) up to 100 (max)	

TABLE AN4.1-2 REQUIREMENTS TRACED TO HEOMD-006 MAIN VOLUME UTILIZATION GOALS AND OBJECTIVES THAT ARE ENABLED

HEO-006 Goal	**SMD Goal 1**: Enable scientific investigations from the lunar surface, including field relationships, in-situ observations, and sample return, to address the multidisciplinary objectives of the Science Mission Directorate			**SMD Goal 2**: Enable scientific investigations from human spaceflight platforms to address the multidisciplinary objectives of the Science Mission Directorate			**STMD Goal 1**: Enable sustainable living and working farther from Earth ("Live")		**STMD Goal 2**: Enable transformative missions and discoveries ("Explore")		**HEOMD Goal 1**: Advance knowledge to support safe, productive human space travel, and enable systems development and testing to reduce health and performance risks for future human exploration					**HEOMD Goal 2**: Advance the operational capabilities required for sustainable lunar operations and the first human missions to Mars including demonstrating approaches to planetary protection.	
Objective	1.1	1.2	1.3	2.1	2.2	2.3	1.1	1.2	2.1	2.2	1.1	1.2	1.3	1.4	1.5	2.1	2.2
Requirement																	
4.1.1	X	X	X	X													
4.1.2	X	X	X	X		X											
4.1.3											X	X	X	X			
4.1.4									X								
4.1.5											X	X	X	X			
4.1.6						X											
4.1.7				X	X	X										X	

AN4.2 XXXXX

<**TBD-008**>

ANNEX-5
INTEGRATED MARS MISSION-SPECIFIC UTLIZATION REQUIREMENTS

<TBD-009>

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